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SIBLEY COLLEGE SERIES

Electrical Engineering Laboratory Notes

For Seniors in E. E.
First Term Work

By V. KARAPETOFF

CORNELL UNIVERSITY
1906

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PREFACE.

These notes comprise the first term's work in the Electrical Engineering Laboratory and are primarily written for Seniors in the electrical engineering course. Seniors in the Mechanical Engineering have a shorter electrical laboratory course and use selected parts of these notes. The experiments described herein may be classified under the following principal headings:

(a) Direct-current machinery;
(b) Alternating-current machinery;
(c) Measuring instruments;
(d) Electric lighting;
(e) Electrical transmission.

Most of the experiments are of a comparatively elementary character; the advanced experiments for Seniors in Electrical Engineering

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This may seem too much guidance, but experience shows that advisable to first acquaint the students with good and efficient metho of testing and experimenting, and then to give them more individua freedom in the advanced stage of their work.

The author wishes to express his appreciation of the assistance tendered to him by the laboratory instructors in reading the manuscripts and the proofs; also for giving him valuable suggestions from their experience.

Cornell University, Ithaca, N. Y.
September, 1906.

The author is greatly indebted to the INTERNATIONAL CORRESPONDENCE SCHOOLS, Scranton, Pa., for their kind permission to use numerous illustrations from their various electrical engineering pamphlets. The cuts taken from these pamphlets are those on pages 22, 23, 26, 42, 43, 49, 51, 75, 76, 78-80, 83-85, 133, 157, 159, 173, 174; also cuts on pages 2-5 of article on the "Telephone Work," and on pages 3-5, 12-16 of the article on "Arc Lamps."

PREFACE.

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(e) Electrical transmission.

Most of the experiments are of a comparatively elementary character, the advanced experiments for Seniors in Electrical Engineering being described in the next installment of the notes.

In describing each experiment the same general plan is followed throughout: first, the practical needs for a certain machine or arrangement of apparatus are indicated; then the object of the experiment and the method of measuring are described in detail; finally definite instructions are given for the manner in which data should be taken in the laboratory.

At the end of each experiment, requirements for the report are stated so that the students will not omit to take all the necessary readings and dimensions while in the laboratory. In addition to these notes, printed data sheets are given the students for putting down their readings systematically, and in the correct order.

This may seem too much guidance, but experience shows that it is advisable to first acquaint the students with good and efficient methods of testing and experimenting, and then to give them more individual freedom in the advanced stage of their work.

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GENERAL REMARKS ON ELECTRICAL LABORATORY WORK.

The right attitude of mind is one of the most essential conditions of success in any kind of work. In application to the laboratory it should mean: "I am coming to the laboratory to get as much information and practical experience as it is possible for me to get; this is for my own interest and I am going to use this opportunity to my best advantage." Without this idea being clearly understood by the students, the best equipment, instructions and instructors are of little value, and it may even be said that the results of the work depend essentially upon the right attitude of mind, for a man who wants to learn will find the necessary information in spite of very adverse conditions.

The Laboratory Notes together with data sheets, additional instructions posted in the laboratory near most of the experiments, and mimeographed requirements for reports give sufficient information for successfully performing the experiments. In addition to these it seems proper to give here some general advice in regard to preparation for the laboratory work,—necessary precautions while performing the experiments and results desired in the reports. It is hoped that these suggestions will help achieve better results and save valuable time.

I. *Preparation for laboratory work.* The success of the experiment and the benefit derived depend essentially on sufficient preparation; without it, too much of the laboratory time is wasted in unnecessary questions, discussions and guess work, and the readings themselves are taken hurriedly and are likely to be unsatisfactory. One of the results of an insufficient preparation is that many interesting phenomena escape attention, and those observed are not interpreted aright. Therefore, before you come to the laboratory prepare yourself as follows:

1. Read carefully the instructions relating to the experiment, and if possible look up the general theory of the particular apparatus.

2. Try to see the apparatus with which you expect to work, before your regular laboratory time; this will help you while reading the notes, as the whole arrangement will be more real to you.

II. *Performing the experiment.* It is difficult to give general advice good for all experiments; special precautions to be observed are given in corresponding instructions. If you are duly prepared for the experiment and know what you are doing and for what purpose, you can be sure to get satisfactory results. To save time and trouble the students will please observe the following:

1. Be careful with the machines and instruments intrusted to your care; we are obliged to charge you the full cost of damages done; moreover, you must remember that in many cases some of you colleagues and friends may be deprived of the benefit of a laboratory exercise because of apparatus having been damaged by you.

2. Many of our direct-current ammeters have external shunts, and some voltmeters have separate multipliers. Connecting into a circuit an ammeter without its shunt or a voltmeter without its multiplier, invariably results in burning out the instrument. It is hardly possible or even desirable to make these instruments fool-proof; at any rate they represent the actual commercial practice. The repair of a burned out instrument is always comparatively expensive, and the students should be careful in using electrical measuring instruments.

3. Do not forget to see that in all cases your circuit is protected from an accidental overload by fuses or circuit breaker of proper size; also be sure that you know exactly which switch to open in case of an emergency. When an electric motor is a part of your scheme, make your connections in such a way that the motor could not run away and do damage.

4. Some of the laboratory exercises naturally imply the use of high-tension currents dangerous to life; the apparatus is, however, arranged so that the students do not need to handle live wires or even come near them. An accident is possible only as a result of gross negligence and will be out of the question if the student will follow this simple rule: *not to touch any live parts of the circuit and always to open the main switch before making any changes.*

5. In coming to the laboratory, bring with you a slide rule, an inch rule or tape, a speed counter, a screw driver and a pair of plyers. This will save you time and trouble of looking for them or borrowing them. Do not forget to have a pocket knife for skinning off wire; a bicycle wrench is also sometimes very handy to have. Have enough clean paper for your sketches, diagrams and remarks.

6. In taking down readings, it is advisable to use carbon paper so as to get a copy for each of your partners; this will save the time of copying the results after the laboratory period. Have some cross-section paper with you, and whenever possible plot approximate curves as soon as the complete set of readings has been taken. In this way all doubtful and contradictory results can be detected at once and their cause made clear; otherwise it may be difficult for the instructor to find out later what was wrong during the experiment, and to help you. Remember that the more care and intelligent effort you exercise in the laboratory, the less trouble you will have in the preparation of the report.

7. In beginning an experiment, start whenever possible from the most difficult conditions: heaviest load, lowest power factor, highest voltage, etc. This for two reasons: first, if you could get a satisfactory reading under such conditions you can be reasonably sure that you will be able to take the whole curve, or at any rate there is enough time to change the instruments, the scheme of connections, etc. Secondly, the points at heavy load or under most unfavorable conditions are usually the most interesting to get, and should anything happen that should prevent you from getting the complete curve, you still will have enough data for a satisfactory report.

8. Should anything go wrong, an instrument be damaged, a bearing or a winding heat, a rheostat burn out, etc., do not try to hide the fact, but report without delay to the instructor. We all know that accidents will happen, and honesty is always the best policy.

9. Always put on your data sheets serial numbers of all the instruments which you use during the experiment. This will help to locate a possible discrepancy or contradiction in your data, and also will enable the instructor to supply you with the right constant after the laboratory period.

III. *Writing up reports.* The report must have as much individuality as possible in order to be of any use at all. After having performed the experiment, discussed the problem during the recitation, and worked out the numerical results, you certainly must get some idea of the subject. All we want from you, then, is to give us the method by which you were working and the results arrived at; if you can add to it some personal observations and remarks, so much the better for you. Please note the following points in particular:

1. Do not repeat in your report things already stated in the Notes: a reference to the page number is sufficient. Where, however, the notes contain the general principle only, it is well for you to explain its particular application in your experiment.

2. In most cases, definite directions are given in notes as to how to plot certain curves. If, however, you find that a particular point can be best illustrated in a different way, you are most welcome to do so. The directions are merely intended to facilitate your work, and not to limit your original thinking and initiative.

3. Criticisms of all kinds are not only desirable in the reports, but will even be considered as increasing the value of the report. Criticize anything you want to: the subject of the experiment, laboratory equipment, method of performing the experiment, laboratory rules, conduct of recitations, etc. All these things are capable of improvement, and we are glad to have your suggestions and remarks. In doing so you will profit by developing a critical point of view in your specialty, and we shall profit by having our attention called to the weak points of our work. Wherever in industrial and commercial establishments, the employees are encouraged to give their suggestions to the management, the results are beneficial for both parties; there is no reason to doubt the same in our institution.

TRANSMISSION AND DISTRIBUTION LINES.

Electric power is usually generated in places more or less remote from where it is used; therefore a *transmission* line is a necessary link between the generating station and the current consuming devices. Where current is consumed in many places, as for instance in various houses of a town, wires supplying power to separate houses constitute the ***distribution*** network, to which the transmission line is connected at suitable places. The above scheme presupposes the most general case, in which power is generated outside of a city, say at a waterfall, transmitted to the city by a high-tension transmission line, converted into low-tension currents and distributed to separate customers. If the power is generated in the city itself, the transmission line is omitted and the power house is directly connected to the distributing network. If the power is transmitted to one place only, say for operating an electric furnace, the distributing network is omitted, there being no necessity for distributing the power to different places.

When an electrical engineer meets the question of a transmission or distributing line it is usually under the aspect of figuring out the cross section of conductors for it. Generally speaking it is merely a question of applying Ohm's law to a given case, but for practical purposes this general law can be reduced to more specific expressions, which bring more into prominence the relations between the quantities under consideration.

This exercise is an experimental study of voltage and current relations in transmission and distributing lines, and of the influence of cross-section of conductors on line loss. Strictly speaking there is no marked difference between a transmission and a distributing line; the subdivision is introduced here merely to indicate simple lines with power consumption at the end only (transmission lines), and complicated networks of conductors with power tapped off at different places (distributing lines). A transmission line can be compared to a trunk railway line, delivering goods at the end only, while a distributing network of conductors is analagous to a system of local branched railways delivering goods at a great many places within a comparatively small area.

1. Transmission line.

The problem in its simplest aspect can be represented thus: *W* kw (Fig. 1) are to be delivered at *B* from a power house situated at *A*; the distance between *A* and *B* is *l* miles. The pressure *E* at *B* must be equal to *e* volts; the pressure at *A* will be somewhat higher to compensate for the pressure loss in the line. It is required to figure out the cross-section of the line conductors. This cross-section naturally depends on the loss allowed in the line. The larger the permissible loss or drop of pressure,—the smaller and less expensive becomes the line. There are, however, several limitations as to the allowable loss in the line. The principal among them are the following:

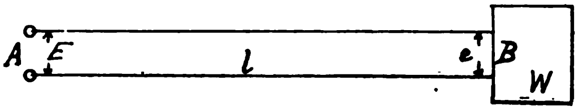

Fig. 1.

1. *Voltage regulation at the receiver end.* The higher the loss in the line the more difficult it is to maintain constant voltage at *B* when the load varies. The drop in the line is proportional to the load so that while at full load the voltage at *B* is considerably lower than that at *A*, the two voltages are approximately equal to each other at light loads. As the switchboard attendant in the power house cannot always follow the fluctuations of the load and adjust the voltage, the pressure at *B* fluctuates considerably, giving a poor service for the lamps as well as for motors.

2. *Energy loss in the line.* The higher the loss allowed in the line the smaller is the original investment in the line copper, but this is to some extent counter-balanced by a continual loss of energy in the line. If coal is high it may be cheaper in the end to have a larger cross-section of conductors in order not to lose too much energy as $I^2 R$ heat in the line. If cheap and abundant water power is available a smaller cross-section may be more economical. The most economical cross-section and loss in the line must in each case be determined separately according to the local circumstances.

3. *Temperature rise in conductors.* Having determined the cross-section of the couductors so as to satisfy the two above named conditions, it still remains to determine if the conductor selected can carry the current

without excessive heating. The smaller the cross-section the less current can the conductor safely carry. The safe carrying capacity of conductors has been determined by experiments, and the results are given in various Engineering pocket-books, Fire Underwritrs' Rules, etc. If the conductor selected is too small for the current, one of the next larger sizes of wire must be taken, which can stand the current without excessive heating.

A few experimental lines are strung in the laboratory for the purpose of experimentally checking results of calculations on cross-section and voltage drop in transmission lines. The materials used in actual lines are copper and aluminum. These are substituted in the laboratory by iron and German silver wires which have a considerably higher resistance; this is done in order to obtain a sufficiently high voltage drop on comparatively short distances. Let us first consider the relations existing in lines carrying direct current.

The principal voltage and current relations in transmission lines are as follows:

If W watts are to be delivered at a voltage e, the line current i is equal to $W \div e$. Suppose the resistance of a wire 1 ft. long and having a cross-section of one mil to be b ohms; then the resistance of a single wire l ft. long and of a cross-section of q c.m. will be

$$\frac{bl}{q},$$

and total voltage drop in the line

$$= \frac{2bli}{q} \text{ or } \frac{2blW}{qe}.$$

Let p be percent drop, or the ratio of the voltage drop in the line to the voltage e. From the above formula it follows that

$$p = \frac{200blW}{qe^2}.$$

Usually two unknown quantities enter into the practical problem: the cross-section q of the wire and the per cent voltage drop p to be allowed. From the above formula the product

$$pq = \frac{200blW}{e^2} = \frac{200bli}{e} \text{..........} (1)$$

can be figured out for any given case; the selection of the proper values for p and q is left to the sound judgment of the designer guided

by the three above mentioned considerations; voltage regulation, energy loss and temperature rise limit. Here, as in most all practical problems, there is an infinite variety of solutions, and engineering skill, feeling and previous experience have to supply the lack of exact mathematical relations.

(1) In order to make clear the physical meaning of the formula select one of the experimental laboratory lines and load it on resistances at a certain voltage e. Measure with a voltmeter the drop in the line and compare it to that given by the above formula. Vary the load and see how the voltage c varies if E is kept constant. If the load contains incandescent lamps, the effect of load fluctuations on the quality of the light will be particularly noticeable.

Take a line of a larger cross-section and repeat the same experiment. It will be found that the line drop will be proportionately smaller and the regulation at variable loads better. If W and e were the same in both cases, it will be found that the product pq is also the same with both lines, as it follows from the above fundamental formula. Now take two lines of different lengths and of the same cross-section; use the same load and voltage on both and determine if the drop and regulation is proportional to the length. This has a great practical importance; you will find that the cost of the line copper increases *as the square of the distance* to which the power is transmitted. Indeed, suppose that it is desired to increase the length of a transmission line twice, for the same amount of power. If the same cross-section of the conductor could be used, the cost of the line would be just a double. But this would give twice the line loss, and if the previous line loss was all that could be allowed for a satisfactory regulation, the new line must have a double cross-section in order to give the same regulation. This in addition to being twice as long, makes the new line four times more expensive than the former one. This law of the squares of the distance is the most serious limitation for the transmission of the power for long distances.

Finally change the voltage at which the power is delivered, for instance from 110 v. to 220 v. According to the fundamental formula, per cent loss is inversely as the square of the voltage; in other words the same power W can be transmitted with only ¼ of the former loss. Or if the previous line loss gave a satisfactory voltage regulation, four times more power can be transmitted with the same line and the same

per cent line drop. This is also a result of prime importance, since it explains the modern tendency towards higher and higher voltages.

In order to see the influence of the material of the conductor (factor b in the formula), the regulation of two lines of different material can be compared. Of the two materials used at present, the conductivity of copper is higher than that of aluminum, but aluminum is much lighter than copper. Taking into consideration specific gravities, conductivities and market prices of the two materials, the cost of a transmission line with the same per cent drop is about the same for both materials. Should aluminum become still cheaper, it undoubtedly will be used on transmission lines in preference to copper.

(2) *Single-phase alternating-current line.* The electrical relations are modified in this case by the influence of self-induction and capacity which may be present in the line or in the load. In all other respects the relations are similar to those described above for D. C. lines. The influence of self-induction and capacity of the line makes itself noticeable only on very long high-tension lines and is taken up in another advanced laboratory problem. We shall consider here the line as having ohmic resistance only.

Referring to Fig. 2 let OB be the vector of the voltage e, Oc that of the current i, lagging behind the voltage at an angle. The voltage drop ir in the line can be represented by a line BA parallel to the direction of the current vecter OC; r is the total ohmic resistance of the line, OA is the voltage E in the power house. It will be seen from this diagram that the voltage drop, AB in the line is subtracted *geometrically* from the station voltage E instead of algebraically as in the case of direct currents. From the triangle OAB we have

$$E^2 = e^2 + i^2r^2 + 2ire \,.\, Cos\phi.$$

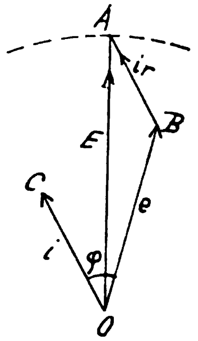

Fig. 2.

This formula or the diagram Fig. 2 takes the place of the simpler relations deduced above for direct current lines. *Suppose, for instance, that it is desired to figure out the cross-section of a transmission line, the power W being consumed at a given power factor $Cos\ \phi$ and at a given voltage e. The voltage drop in the line must not exceed p per cent of e.

---

* It is self-evident however, that if the load is non-inductive formula (1) can be used for figuring out alternating current lines.

Construct OB and OC and from O strike an arc of a circle with a radius $E = (1 + p / 100)\, e$. Draw the line BA parallel to OC; the point A of its intersection with the arc gives the length $BA = ir$. Knowing i, the resistance r of the line can thus be determined, and the cross-section of the conductor found from the formula

$$r = \frac{2bl}{q}.$$

It will be seen from Fig. 2 that in case of an inductive load, per cent voltage drop and per cent regulation are different. Take for instance the extreme case of a purely inductive load (Fig. 3), and suppose that the line drop BA is equal to 30% of OB. Then the power house voltage E is

$$OA = \sqrt{e^2 + (0.30e)^2} = e\sqrt{1.09} = 1.044e;$$

in other words the difference between E and e is but 4.4%. If the load were non-inductive the voltage E should be 30% higher than e, as shown by the vector OA'.

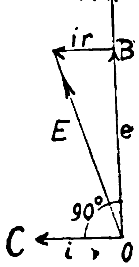

Fig. 3.

It is desired that the students make clear to themselves these fundamental relations by selecting a few different loads, inductive and non-inductive and taking measurements necessary for the construction of diagram Fig. 2. The best way is to keep the current constant so as to have the same line drop ir. It will be found that the difference between E and e is smaller the lower the power factor of the load.

This, however, should not be understood in the sense that the lower the power factor the more favorable are the conditions for transmitting power. On the contrary a lower power factor means a higher current for the same power transmitted, and therefore a larger line drop and I^2R loss. The former result was due to the fact that *the line current was kept constant,* allowing it to become more and more wattless. Now take another set of readings *keeping the power transmitted constant* (as shown on the wattmeter) and making the load more and more inductive.

This corresponds closer to the actual state of affairs and it will be found that the regulation on inductive loads is worse than on non-inductive.

3. *Branched transmission line.* In many cases power generated in a power house has to be transmitted to several localities. If independent transmission lines are used for each locality, the problem is solved

for each transmission line separately. Sometimes, however, it is more economical to use a common transmission line for at least a part of the way (Fig. 4), and then divide it into several branches. Fig. 4 represents a case where power generated at A is transmitted by a common line to D, and thence branched to towns B and C.

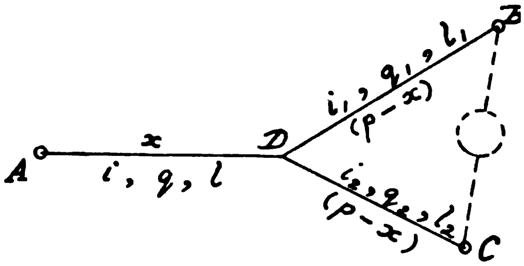

Fig. 4.

The problem is to determine the cross-sections of the three parts of the transmission line so as to have *a minimum weight* of line conductor, for a given total drop of voltage between A and C or A and B. Assume as before the voltage at B (and at C as well) to be e, and the total drop between A and B to be as before $= p\%$. The only unknown quantity is the % drop x between A and D; if this be known, the per cent drop $(p - x)$ in the branches DB and DC will also be known, and each conductor can be calculated separately by the fundamental formula (1) given above. The drop can be calculated as follows: according to the conditions of the problem we have

$$ex = \frac{200ibl}{q} \dots\dots\dots\dots (2)$$

and also

$$e(p - x) = \frac{200i_1bl_1}{q_1} = \frac{200i_2bl_2}{q_2} \dots\dots\dots\dots (3)$$

The total weight of the line is proportional to

$$P = ql + q_1l_1 + q_2l_2,$$

or substituting in it the values for q, q_1, q_2 from the above equations

$$(1 \div 200)\, P = \frac{ibl^2}{ex} + \frac{i_1bl_1^2}{e(p-x)} + \frac{i_2bl_2^2}{e(p-x)}\,.$$

The weight is minimum, when $\frac{dP}{dx} = 0$, or

$$-\frac{il^2}{x^2} + \frac{i_1 l_1^2}{(p-x)^2} + \frac{i_2 l_2^2}{(p-x)^2} = 0$$

whence

$$\left(\frac{x}{p-x}\right)^2 = \frac{il^2}{i_1 l_1^2 + i_2 l_2^2} \quad \ldots\ldots\ldots\ldots (4)$$

The quantity of x can be easily calculated from this equation; after this the cross-sections of the three parts of the line are figured out from the formulae (2) and (3).

In order to make the meaning of this rule (4) of copper economy more real, three experimental transmission lines similar to that shown in Fig. 4 are arranged in the laboratory. They are all of the same length, but the cross-sections of the three parts are different in each line. In one line the ratios are selected so as to nearly satisfy the above rule (4) of minimum weight, in two others the percentage drop x is either too large or too small.

If it were possible to have exactly the same load and the same voltage drop in all three cases, it would not be necessary to reduce the weight of the line on the basis of one ampere and 1% loss. It is simpler not to try to have absolutely the same data in the three runs, but reduce them afterwards. This is correct since the cross-section of the conductors is proportional to the drop allowed in the line, as it follows from the formula (1). In each case, however, it is absolutely essential that the drop *A—B* be the same as *A—C,* since this condition was presupposed to be fulfilled in deducing the rule of the copper economy. In order to be sure that this is actually fulfilled during the test, it is advisable to have a low-reading voltmeter connected between *B* and *C*; the load to be adjusted so that this voltmeter reads zero. Or else a low-resistance wire can be connected between *B* and *C,* so as to practically equalize the voltages.

Make the measurements described above in the following order:

(1) *Analysis of the formula (1) for direct-current lines.* Select one of the laboratory lines and load it up so as to have a certain drop p. Vary the load and take a curve of line drop as a function of the load. Repeat the same experiment with a line of a larger or a smaller cross-section.

Take a line having the same cross-section as in the first run, but of a different length; take for this line a curve of line drop as a function of the load.

Repeat one of the above runs at a different voltage.

(2) *Single-phase alternating-current line.* Take a line and load it on a combination of ohmic and inductive resistances. Vary the load so as to keep the total current constant, with the power factor variable, Take a curve of line drop and regulation as a function of the power factor.

Make a similar run, this time keeping total watts constant and varying the power factor.

(3) *Branched transmission line.* Take a line similar to that shown in Fig. 4, and load it at B and C, taking care that the voltage at these two points be the same. Read the currents and the voltage drop in the three parts of the line. Repeat the same experiment with two other transmission lines of the same form; try to have nearly the same load and the same voltage drop in all three cases.

Before you leave the laboratory, measure the lengths and the cross-sections of all the lines with which you were working.

In your report give the following results:

(1) Plot your curves showing that the line drop is proportional to the load. Give data which proves that for the same load the drop is inversely proportional to the cross-section of the conductor, and directly proportional to its length.

Show on the basis of your data that when the voltage of transmission is increased, more kw can be transmitted through the same line with the same percent line drop. Work out backward the conductivity b of the line material from the formula (1), and compare it to that given in pocket-books.

(2) Plot to power factor as abscissae the curves of voltage drop and regulation:— (*a*) for constant line current, (*b*) for constant watts output. Construct a vector diagram (Fig. 2) for a certain value of power factor and compare voltage drop and regulation to those actually observed.

(3) For the branched transmission line show from your experimental results that the weight of line material is a minimum, when the cross-sections of the three parts are selected as required by the rule (4) proved above.

NOTE.—The above investigation refers to direct-current and single-phase lines only. Most modern long-distance transmission lines are *poly-*

phase lines (two-phase or three-phase). So far as the line drop, regulation and determination of the cross-section of conductors are concerned, the above formulas can be applied to polyphase lines with the following changes:

A *two-phase line* can be considered as a combination of two independent single-phase lines each carrying one-half of the load (Fig. 5).

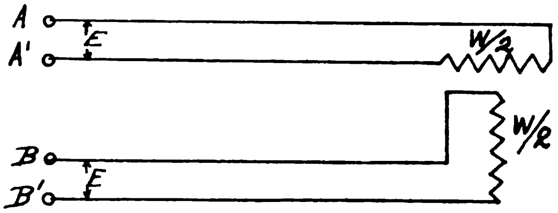

Fig. 5.

Thus the cross-section of each conductor is only one-half of what it would be for a single-phase line, but as there are four conductors instead of two the total weight of the line is the same as for the single-phase line.

Similarly, a *three-phase line* can be considered as a combination of two lines, say *A* and *C*, (Fig. 6), the conductor *B* being their common return wire. Therefore *A* and *C* need only have one-half the cross-section of a single-phase line carrying the same total load *W*. The wire *B* must have the same cross section as *A* and *C* because the return current is equal to each of the line currents, and any of the three wires can be considered as a return wire. From this it follows that total weight of the conductors in a three-phase line is but 75% of the weight of an equivalent single-phase line.

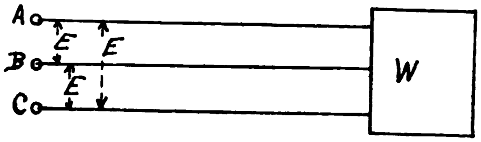

Fig. 6.

Thus, whether you have a three-phase or a two-phase line, figure out the cross-section of the conductors as if it were a single-phase line having the same total load *W*, the same distance of transmission and the

same permissible voltage drop. Then for polyphase transmission use wires of only one-half cross-section,—four wires for two-phase lines, three wires for three-phase lines.

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2. Distributing Network of conductors.

As was explained above, the principal distinction between a distributing line and a transmission line is that the latter is loaded at its end only, while the former has customers taking power from it at different places (Fig. 7). We know now how to figure out the cross-section of a conductor loaded at its end only; the problem to be studied in connection with the distributing network will be: determining voltage drop and cross-sections of conductors loaded at different places.

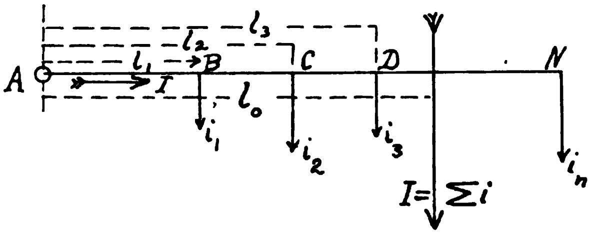

Fig. 7.

To make the conditions closer to the actual practice a model is provided in the laboratory, representing part of a city, with streets, houses and electric wiring. In order to simplify the model only one side of the lines (say positive) is strung on its face; the other side made of negligeable ohmic resistance, is concealed on the back of the board. In reality, of course, positive and negative mains have the same resistance, so that voltage drop observed on the model should be doubled up to represent the actual conditions.

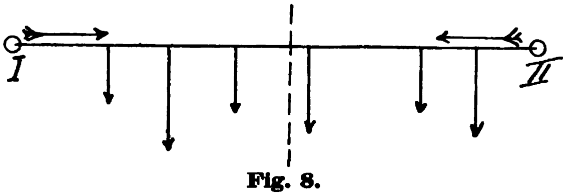

Fig. 8.

The network is laid out so that the principal combinations met with in practice are shown, viz.;

(1) Conductors fed from one end (Fig. 7);
(2) Conductors fed from two ends (Fig. 8);
(3) Ring or mesh conductors (Fig. 9).

City networks are usually laid so that as many street conductors as possible are fed from at least two points, as shown in Fig. 8; in case of an accident to one of the feeders all the customers can still temporarily be supplied from the other feeder, even if the service be not as satisfactory because of a greater voltage drop.

The experiment consists in loading the network in various combinations and in studying the resulting current and voltage relations. For measuring voltages a double scale voltmeter is provided, the 150 v. scale being used for measuring the pressure across the line, and the 3 v. scale being used for measuring the drop along the line. The students must be careful not to burn out the instrument by connecting the low reading terminals across 110 v. supply.

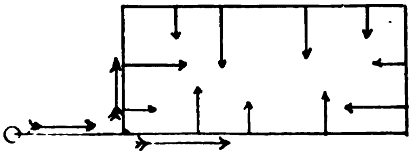
Fig. 9.

As it would not be feasible to have many ammeters inserted for measuring currents in the various places of the network, the following simple scheme (Fig. 10) is used, by means of which currents can be measured in each conductor. High resistance German silver wires are used on the model instead of ordinary copper wire, in order to obtain a sufficiently large drop of potential on comparatively short distances. These German silver wires themselves are used as ammeter shunts, and the current is measured by a milli-voltmeter connected across a certain length of the conductor.

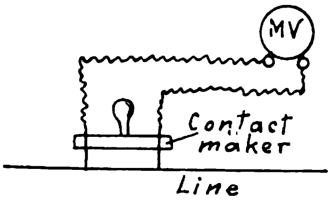

Fig. 10.

In order to have a direct comparison this length must be exactly the same in all cases, and this is obtained by means of a special contact-maker (Fig. 10) whose knife edges are set at a certain distance. With this arrangement the magnitude and the direction of the current in each

conductor can be easily measured. The readings are directly comparable only if the same size wire is used throughout. In reality two sizes of German silver are used on the model, No. 14 and No. 20, the former having a cross-section 4 times that of the latter. Therefore if the millivoltmeter was calibrated in amperes with No. 14 wire, its indications must be divided by 4 when using it on No. 20 wire.

In order to be able to account for the observed phenomena on the model, let us first deduce the fundamental formula of voltage drop for a conductor loaded as in Fig. 7; this will be a formula analogous to formula (1) for transmission lines.

With the same notations as before, and referring to Fig. 7 we have that for the customer N situated the farthest from the distributing point, the voltage drop can be represented by the formula

$$\frac{pe}{100} = \frac{I.b.2l_1}{q} + \frac{(I-i_1).b.2(l_2-l_1)}{q} + \frac{(I-i_1-i_2).b.2(l_3-l_2)}{q} + \ldots\ldots$$

Here the first term represents the voltage drop along AB, the second along BC, *etc.* After simple mathematical transformations the formula can be reduced to

$$\frac{pe}{100} = \frac{2b}{q}(i_1l_1 + i_2l_2 + i_3 \times l_3 + \ldots)$$

of finally to

$$pq = \frac{200\,b\,\Sigma\,il}{e} \quad \ldots\ldots\ldots\ldots(5)$$

This formula is perfectly analogous to (1) and like it is used for determining the cross-section of conductors when the load is given, or for determining the load that a given conductor can carry under the condition that a certain voltage drop should not be exceeded.

The expression (5) shows that the cross-section of, or the drop in a conductor loaded at several places depends not only on amperes load, but on *the position of the load* as well. A small load situated far from the feeder may affect the line drop just as much as a comparatively heavy current taken near the distributing point. In other words *load in distributing lines is measured not by amperes or watts but by ampere-ft.*

It is customary in practice to measure load by the number of 16 c. p.

lamps instead of amperes; the unit *lamp-ft.* is therefore used as much as ampere-ft. To show how simple is the application of the formula (5) suppose that it is required to figure out the sizes of street or house conductors in a part of a city, the maximum drop allowed being 2%, and the pressuse 100 v. For copper conductors b = about 10 ohms; a 100 v. 16 c p lamp consumes about 0.5 amp, and we have

$$q = \frac{200 \times 10 \times 0.5 \, \Sigma \, Ll}{100 \, . \, 2},$$

or

$$q = 5 \, \Sigma \, Ll,$$

where number of lamps L is introduced instead of amperes i.

Thus knowing the number of lamps to be connected at different places along a certain conductor, its cross-section can be easily found from this simple formula.(*)

When a conductor is fed from two ends, (Figs. 8 and 9) there is always a point of division, on one side of which the customers are supplied with current from one feeder, on the other side from the other feeder. The position of this point naturally depends on the instantaneous load and is always such that Σil is the same on each side of the point. In figuring out the cross-section of a conductor fed from two ends, all customers should be supposed connected simultaneonsly and the point of division determined under these most unfavorable conditions. Then the conductor can be supposed cut in two at this point and the cross-section of each half figured out independently from the formula (5). The larger of the two sizes figured out for the two halves should be then taken for the whole conductor.

When a line becomes overloaded by adding new customers, it becomes necessary to either increase its cross section by paralleling it with another line, or to add a new feeder. One or the other solution is preferred in practice according to the conditions of a particular case. In order to see the influence of an extra feeder, a suitable connection is provided on the model. Having loaded the line with one feeder and measured the maximum drop at the lamps farthest from the feeder, add another feeder. It will be found that the conditions will be materially improved and the voltage drop considerably reduced.

*** Instead of the expression Σil a simpler expression $l_0 \Sigma i$ is often used in practice; l_0 is the distance to the center of the load, considering i_1, i_2, ... as forces applied at the distances l_1, l_2, ... (Fig. 7.)**

In some cases voltage is different at different feeding points because the feeders themselves have different cross-sections, different lengths and carry different loads. In such cases, the feeder with a higher voltage carries a proportionately larger part of the load. The above rule, that the point of division of the load is determined as in Fig. 8 is only true when the same voltage is maintained at I and II. If for some reason, voltage at II is a per cent higher, we have according to the formula (5)

$$p = \frac{200 b \, (\Sigma il)_{\mathrm{I}}}{qe},$$

and

$$a + p = \frac{200 b \, (\Sigma il)_{\mathrm{II}}}{qe}.$$

Subtracting one equation from the other we get

$$aq = \frac{200 b}{e} \left[(\Sigma il)_{\mathrm{I}} - (\Sigma il)_{\mathrm{II}} \right] \text{............} (6)$$

When $a = 0$, this is reduced to the former condition $(\Sigma il)_{\mathrm{I}} = (\Sigma il)_{\mathrm{II}}$ Formula (6) determines the position of the point of division of the load, when there is a difference of potential $a\%$ between the feeders. By inserting some resistance in one of the feeders part of its load can be transferred to other feeders and *vice versa.*

The following experiments can be performed with this model of a city network of conductors:

(1) Trace out the voltage drop along a line fed from one end, measuring the voltage drop from the feeding point to each customer and all the currents, in the line, as well as those taken by the customers.

(2) Connect to the line a customer near the feeder and another one as far from the feeding point as possible . Measure the voltage that they get as other customers are gradually connected to the line. This should illustrate that the customer at the end of the line is affeced by the fluctuating load much more than the customer at the beginning of the line.

(3) Now investigate the influence of the factor Σil on voltage drop to the last customer. Connect to the line a certain number of lamps near the feeding end and then near the opposite end of the line. Meas-

ure in both cases the voltage at the terminals of the last customer. It will be found that the same number of lamps affect his voltage differently in the two cases. Now change the number of lamps in one of the groups until he gets the same drop in both cases. Verify that in this case the number of ampere-ft. is the same in both groups of lamps.

(4) Load the line as under (1) and then add a feeder at the opposite end of the line. Adjust the feeders so that the voltage at both feeding points be the same, and take again the same readings as under (1). Also determine the point of the division of the load.

(5) Now keep the voltage at one of the feeders a little higher and take the same readings. Find the new position of the point of division of the load.

(6) Take a ring conductor, load it and find the maximum voltage drop. Now convert it into a conductor fed from one end, by disconnecting one end from the feeder and see how much more voltage drop you get. Also notice that now a different customer than before gets the largest voltage drop. This corresponds to the case, when the fuses in one feeder should blow out and the line be temporarily supplied from one end.

In your report give the following results:

(1) Plot to conductor lengths as abscissae, voltage drop as shown in Fig. 11. Curve *A* refers to a conductor fed from one end, *B* fed from both ends at the same voltage and *C* when the feeder at II has a voltage *a* per cent higher than that at I.

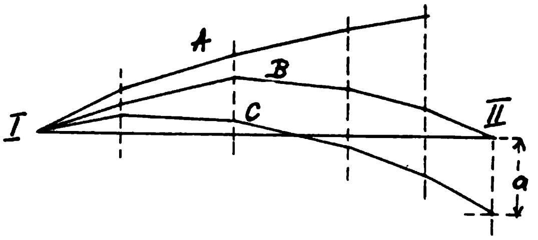

Fig. 11.

(2) Show from the observed data that the voltage drop for the line fed from one end is the same for different distribution of the load as long as Σil is the same.

(3) Check the voltage drop observed in the line fed from one end to that given by formula (5).

(4) Show that the point of division of the load as found during the experiment satisfies the condition $(\Sigma il)_{\mathrm{I}} = (\Sigma il)_{\mathrm{II}}$ when the two feeding points are maintained at the same potential, and that this point is in accordance with the formula (6), when this potential is different.

(5) Give your data in regard to voltage drop in the ring conductor, operated under normal conditions, and when one of its ends is opened.

INTEGRATING WATTMETERS.

As is known from the general theory of electricity, electric power in D. C. circuits is measured by the product, volts times amperes (Fig. 1). Where the conditions are steady an ammeter and a voltmeter can be used; the product of simultaneous readings give true watts. This however is not so with alternating currents when the load is inductive, as in this case the true power equals *IE.Cos* ϕ, where ϕ is the angular displacement between the current and the voltage waves. Moreover it is not cenvenient to use two instruments, especially on fluctuating loads. as it is difficult to read them simultaneously. Finally for practical purposes it is much more convenient to have direct readings in watts instead of every time mutiplying volts by amperes.

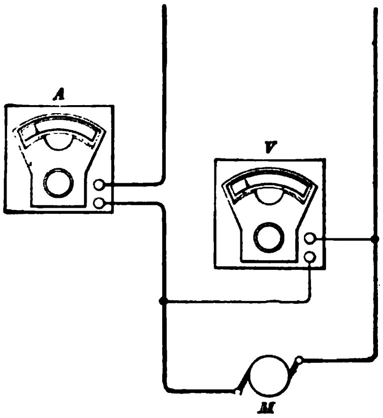

Fig 1.

The instruments which are a combination of an ammeter and a voltmeter in one instrument and read directly in watts are called wattmeters (Fig. 2). A wattmeter has two separate windings and two pairs of terminals. The terminals *d-d,* belong to the series or ammeter winding and are connected in series with the line; the terminals *e-e* belong to the shunt or voltmeter winding and are connected across the circuit. The disposition of these windings is shown in Fig. 3.

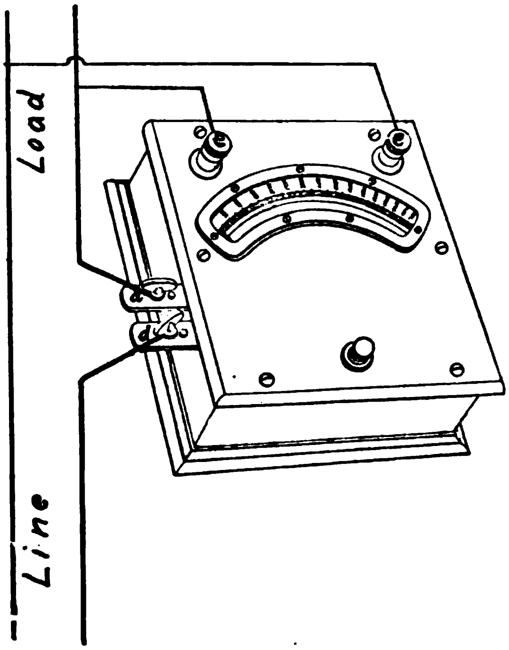

Fig. 2.

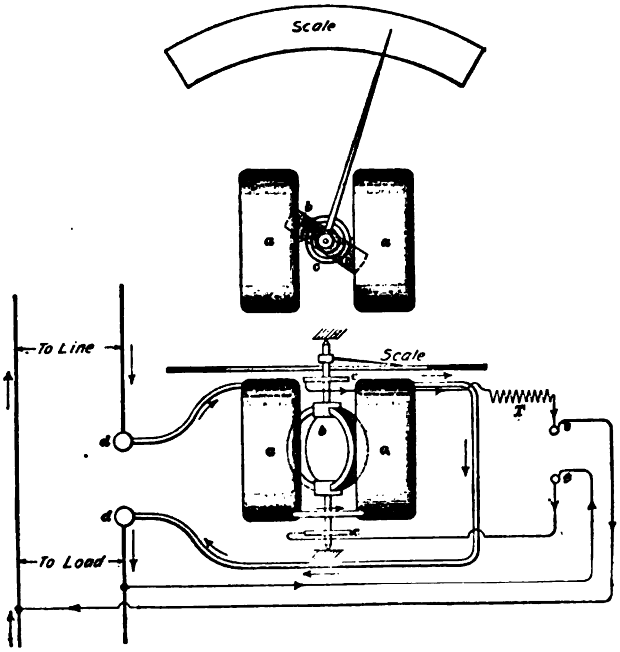

Fig. 3.

The coils *a-a* of the series winding are stationary, the shunt coil *b* is pivoted inside of the stationary windings and is retained in zero position by two spiral springs *c-c,* which are also used for leading in current into the moving coil. *T* is a high resistance or the multiplier in series with the potential coil *b;* it is used here for the same purpose as in voltmeters, viz., to keep down the current in the potential circuit.

The above described wattmeter shows the true watts on direct as well as on alternating current circuits, on inductive or non-inductive loads since the force of attraction between the stationary and the moving coil is proportional to the product of the instantaneous values of the currents flowing in these coils. This type of wattmeters is called ***indicating*** wattmeters, to distinguish them from ***integrating*** wattmeters, which show not the instantaneous watts, but *watt-hours* spent in a circuit during a certain period of time.

The principal application of integrating wattmeters is on customers' premises, since the charge for electric light and power is in most cases made per kilowatt-hour. It takes a certain amount of coal to develop 1 hp. or one kilowatt during one hour, and it is therefore natural that the unit price for the use of electric power should be expressed in the same units. Large integrating wattmeters are also installed in generating stations in order to have an account of the power generated and to be able to figure out its cost at the bus bars.

Integrating meters are much more used in practice than indicating; the purpose of this laboratory exercise is to study the construction and operation of the principal types of integrating meters on the market; this will also give the students an opportunity to learn the calibration and the handling of integrating wattmeters and to see the factors which affect the accuracy of calibration.

Meters used at present are of motor type almost exclusively; a small motor being so arranged as to revolve at a speed proportional to the energy passing through it. The number of revolutions is recorded on a dial, and by knowing the constant of the meter this number of revolutions can be reduced to kilowatt hours. In most meters the shaft of the motor is geared to the recording mechanism is such a way that the meter reads direct in kilowatt-hours.

For direct-current service commutator-motors are used in integrating wattmeters; for alternating current service, single-phase induction motors. Commutator meters can be used on alternating-current circuits

also, but as the induction meter is much simpler and more reliable in operation, it is now used for alternating current work almost exclusively.

1. Commutator meters.

The commutator meter (Fig. 4) consists of a small direct-current motor having a vertical shaft, and without iron in its magnetic circuit.

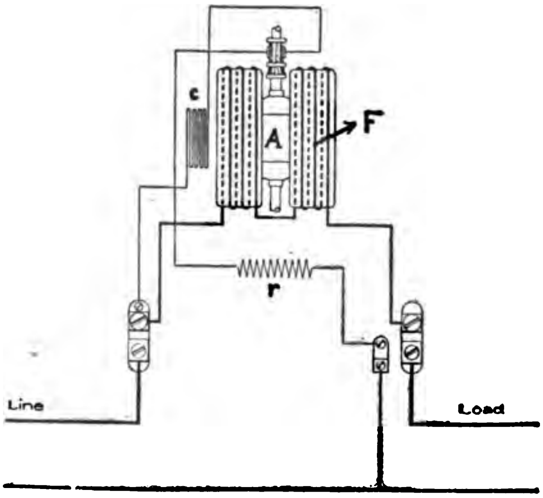

Fig. 4.

The armature, A, is connected across the line with some additional resistance, r, in series according to the magnitude of the supply voltage; the fields, F, are in series with the line. Thus the current flowing through the armature is proportional to the line voltage, and the current flowing through the field is equal to the line current; hence the attraction between the field and the armature is proportional to the product "line voltage times line current," or proportional to the energy delivered. In this respect it is similar to the indicating meter shown in Fig. 3. Fig. 5 gives the general view of this meter. The motor connected in this way would run away without a load. To make its speed proportional to the energy transmitted, it has a Foucault-current brake, consisting of a copper or aluminum disk, *D,* mounted on the armature shaft and placed between the poles of permanent magnets *MM* (Fig. 3). To understand the action of this brake, assume first that the meter has no friction and that the armature revolves at the full rated load at a certain speed determined by

the counter-torque of the eddy-current in the brake. Now if the load, or the product volt-amperes falls say to ¾ of its former value, the attraction between the field and the armature of the motor drops in the same

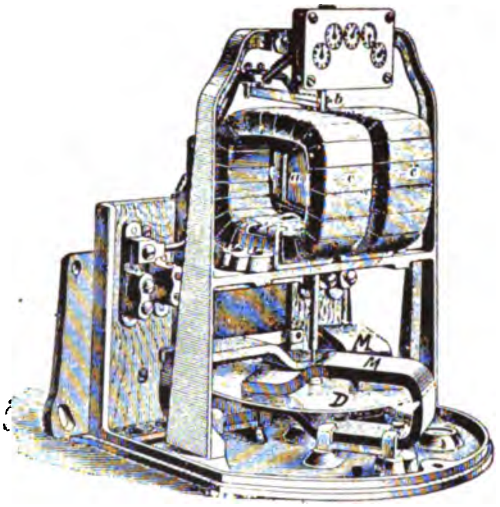

Fig. 5.

ratio and the motor slows down. This decreases the eddy currents (which are proportional to the speed) in the brake and at ¾ of the initial speed the counter torque is again equal to the motor torque. Thus without friction the speed would be proportional to the load, and the motor would register correctly at all loads.

Friction causes the meter to run too slow on small loads, and as in a great majority of cases the meter has to run on light load most of the time, this represents an appreciable loss to the company supplying the current. For instance, a 20-lamp (10 amp.) meter would not start at all (without a compensating device described below) if only one or two lamps were burning, which fact might induce the customer to leave a lamp or two permanently in the circuit.

To remedy this, a compensating coil *c* (Fig. 4) is provided in the armature circuit, the field produced by this coil giving an additional torque just sufficient to balance the friction of the meter. As it is impossible to predetermine the exact amount of friction, the more that it varies

with the pressure of the brushes on the commutator, with the wear of the jewel supporting the shaft, etc., this compensating coil is made adjustable. The complete arrangement is shown in detail in Fig. 6. *FF* are the main field coils, *K* is the compensating coil. Its distance from the armature can be varied by means of screws *A* and *B* and guides *C* and *D*.

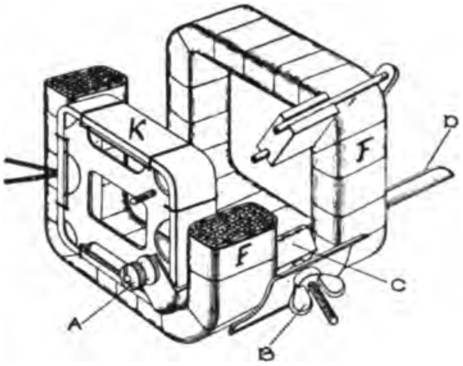

Fig. 6.

In some meters the compensating coil is stationary, but is provided with several taps connected to the buttons of a dial. By means of a small lever more or less turns of the compensating coil can be introduced into the circuit and in this way the amount of compensation varied at will.

If the meter is not sufficiently compensated, the company is losing money on light loads; if the meter is over-compensated, it *creeps* at no-load and registers energy even when no current is used. This naturally leads to a complaint on the part of the customer; he refuses to pay the bill, becomes prejudiced against using electric power and the company is again losing money. It is commonly appreciated now that honesty in regard to meter calibration and adjustment is the most profitable policy on the part of illuminating companies (and the best advertisement for obtaining new customers.)

The speed of the meter should be so adjusted so as to give a direct reading on the dial or simple multiples as 2, 10, etc. This can be done by adjusting the position of the permanent magnets of the brake so as to get the required amount of eddy currents induced in the brass disk. A sample of a meter dial is shown in Fig. 6*a*; with the position of the hands shown there the reading is 2,158.1 K. W. hours. If the reading next month, for instance is 2,172.2, the consumption during the month was 14.1 K. W. hour and at a price of say 12c per K. W. hour, the monthy bill will amount to $1.69.

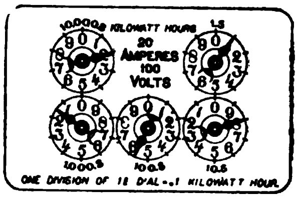

Fig. 6a.

It can be seen from Fig. 4 that one of the series or current terminals can be used at the same time as one of the terminals of the potential circuit. The connection can be made inside of the meter so that only three terminals are visible on the outside (Fig. 7).

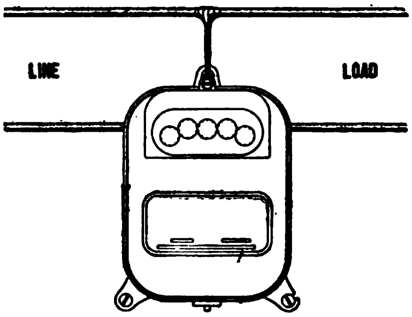

Fig. 7.

The above described commutator meter has two drawbacks:

(1) The commutator with its brushes is always the unpleasant part of every electrical apparatus, as it is liable to give trouble or get out of order. This is of particular importance in the case of integrating meters which are sealed and placed on customer's premises, and thus cannot be conveniently watched.

(2) Absence of iron necessitates a comparatively large number of turns on both windings; this makes the moving part heavy, increases bearing friction and causes jewel troubles.

These two objections are eliminated in an original integrating meter

recently put on the market under the name of "Sangamo" meters. It is in its principle (Fig. 8) a homopolar electric motor, the armature

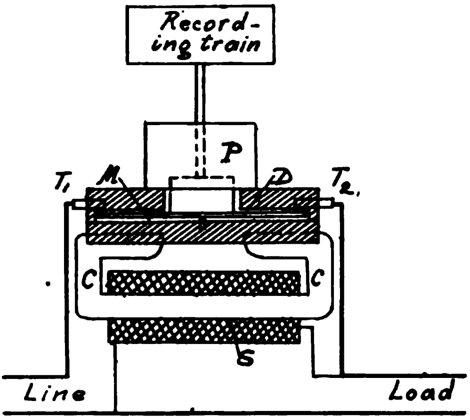

Fig. 8.

of which floats in mercury and is subjected to a comparatively strong field of a shunt coil provided with an iron core. Main current passes from the terminal T_1, through mercury M to the armature D, which consists merely of a copper disc, floating in the mercury; hence the current passes to the terminal T_2 again through the mercury. The magnetic field is produced by the iron core CC energized by the coil S; which coil is connected across the line. Thus the field of this meter is proportional to the voltage of the supply, and the armature current is equal to the current to be measured. The attraction between the armature and the field is thus proportional to volts times amperes or to the energy to be measured. This meter is provided with an eddy current brake (not shown in Fig. 8) similar to that described above, and so its speed is proportional to the watts consumed in the load circuit.

This meter has no commutator or brushes so that this trouble is obviated; the armature is much simpler and lighter than that of commutator meters, and, moreover, its weight does not rest on the lower bearing, since the disc is floating in mercury and is balanced so that there is just a little buoyancy upward. A strong field makes it possible to obtain a higher torque and thus make the action of the meter more positive on light loads. Whether these advantages are counterbalanced by the presence of mercury, and how satisfactory the meter will prove under

severe conditions of actual service cannot be judged now; at this writing Sangamo meters are just being put on the market.

A shunt is provided around the terminals T_1, T_2 for adjusting the meter. By varying the resistance of this shunt, a certain part of the main current can be made to pass around the mercury and disc instead of through them. P is a pocket having such a form that the mercury cannot possibly be spilled out in any position of the meter during transportation.

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2. *Induction meters.*

Alternating current integrating wattmeters are in their underlying principal single-phase induction motors, and operate on the principle of the revolving magnetic field. The general arrangement of the circuits in one of the popular makes of this meter is shown in Fig. 9. As in every wattmeter, there are two windings, one in series with the main

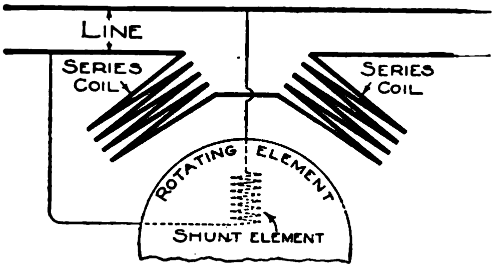

Fig. 9.

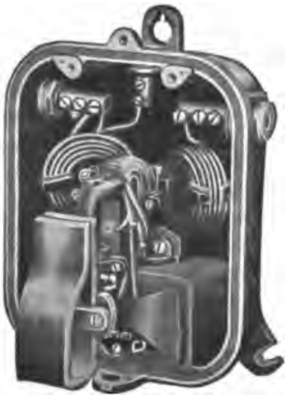

Fig. 10.

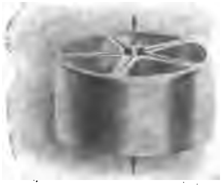

Fig. 11.

current, another shunted across the line. In induction meters both these windings are stationary and produce together a revolving magnetic field in which a light aluminum armature revolves, as a squirrel cage rotor of an induction motor. The two windings are clearly seen in Fig. 10; Fig. 11 represents the revolving aluminum armature of the meter.

In order to make the speed of the meter proportional to the load an eddy current brake is provided as in commutator meters. Only here it is not necessary to have a separate disc on which permanent magnets would act. The same aluminum rotor can be used as the brake armature (Fig. 12); this makes the meter less expensive and more compact than direct current meters.

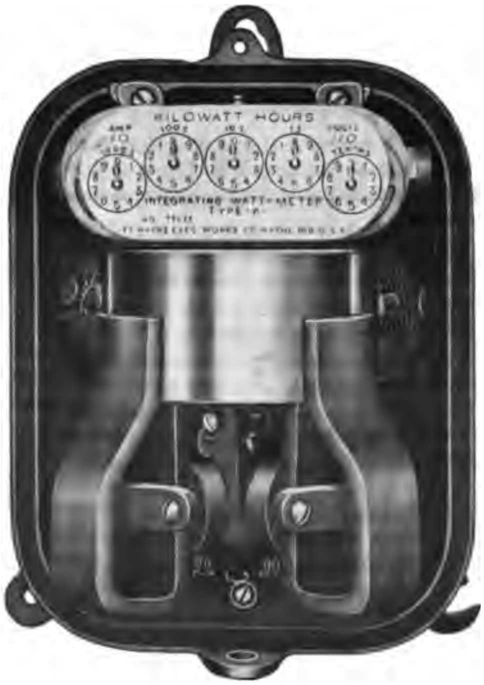

Fig. 12.

The explanation of the working principle of induction meters is as follows. If the currents in the series and the shunt windings of the meter (Fig. 9) were in phase, the magnetic fluxes which they produce would also be in phase and would give a resultant pulsating flux. The

currents induced by this flux in the aluminum armature would be symmetrical with respect to the windings and there would be no reason why the armature should begin to revolve one way or the other.

But in reality the self-induction of the shunt circuit is much higher than that of the series circuit, so that at non-inductive loads the current and the flux in the shunt circuit lag considerably behind the current and flux in the series circuit; thus the currents induced in the armature become unsymmetrical and it is set in rotation. The greater the difference in phase between the series and the shunt field the stronger the pull on the armature, and it is therefore natural that at non-inductive loads this difference should be 90°; then the meter will record correctly at any other power factor, and when the power factor is zero the meter will stand still as it ought to do, there being no actual *power* in the circuit.

In order to obtain an angle of lag as near as possible to 90° the shunt circuit of induction meters is made as highly inductive as possible by connecting an induction coil in series with the shunt winding of the meter. But still this leaves an angle somewhat less than 90° because

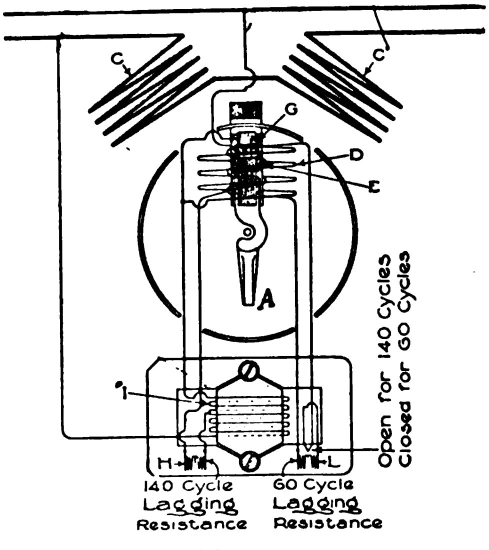

Fig. 13.

of the influence of the ohmic resistance of the coils; therefore modern meters are provided with some kind of correcting or compensating device,

which brings the shunt flux in exact quadrature to series flux at non-inductive loads.

In the meter under discussion this is accomplished by an additional shunt winding as shown in Fig. 13. *CC* is as before the series winding, *D* is the shunt winding connected across the line through an inductance coil *I*. *G* is the above mentioned compensating coil for bringing the shunt magnetism in exact quadrature to series magnetism. This coil is connected across a few turns of the inductance coil *I* and placed inside the shunt coil *D* on a separate iron core. Resistance *H* in series with the compensating coil (lagging resistance) is adjusted so that the meter stands still at a full inductive load; this is a check for the compensation.

A third winding E is shown in Fig. 13, short-circuited on itself through an adjustable resistance *L*. This makes it possible to use the same meters with two standard frequencies: 60 cycles and 140 (or 133) cycles. When the meter is used on a high-frequency circuit, the coil *E* is inoperative; but when the meter is connected into a 60 cycle circuit the compensation offered by the coil *G* is not sufficient. Then the circuit of the coil E must be closed and the resistance L adjusted until again the meter stands still at a purely inductive load.(*)

In describing commutator meters the light load adjustment or the friction compensating winding was mentioned. This light load adjustment is of much less importance in induction meters since their moving element is lighter and the torque per unit weight of the moving element much higher, so that the influence of the pivot friction is not so marked The necessary compensation in the meter under consideration is obtained by merely making the field initially somewhat unsymmetrical, so as to give the armature a one-sided pull just sufficient to balance the friction. In the meter under consideration the phase-correcting coil G is wound on a movable arm A, and this arm can be set in such a position that the meter will surely start at a certain small percentage of full load.

Another construction of an induction meter is shown in Fig. 14. The lower coil is the series coil; *BB*—two potential coils. The armature has the form of a disc (not shown in Fig.) and revolves in the space

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* It would be hardly possible in practice to obtain a load at a power factor of O; therefore this adjustment is done on a two-phase circuit. The series winding of the meter is connected to one phase through a non-inductive load; the potential winding is connected to the other phase, which is exactly in quadrature with the first phase. In this way conditions are created that would take place in a theoretically pure inductive circuit.

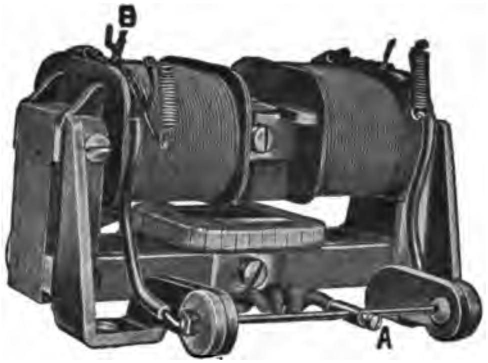

Fig. 14.

between the series and the potential coils. Compensating coils are wound on the same spools with the shunt coils *B,* and are short-circuited upon themselves through a resistance. This resistance can be adjusted by means of the slide contact *A* so as to bring the shunt flux in its correct quadrature position. No friction compensating device is provided in this meter, but the friction is reduced to a negligeable amount by having the moving element exceedingly light; moreover, the lower end of the shaft rests on a steel ball instead of a jewel, thus substituting the rolling friction instead of the ordinary jewel friction.

The Sangamo meters before described, can also be used on alternating-current circuits. These meters are based on the principle of direct attraction between the armature and the field; therefore the field flux must be in phase with the armature current (at non-inductive loads) instead of being in quadrature with it as in induction meters. As, however, the shunt winding possesses some self-induction it is neutralized by connecting some capacity (a condenser) in series with it, so as to make the circuit practically non-inductive. The iron circuit must of course be laminated. In all other respects the D. C. and the A. C. Sangamo meters have the same construction.

Polyphase integrating meters are merely a combination of two single-phase meters, whose armatures are mounted on the same shaft and act on the same recording train, thus automatically adding together the indications of the two component meters. Some polyphase meters have separate magnets and separate armature for each component meter; in some constructions however (Fig. 15) both component meters act on

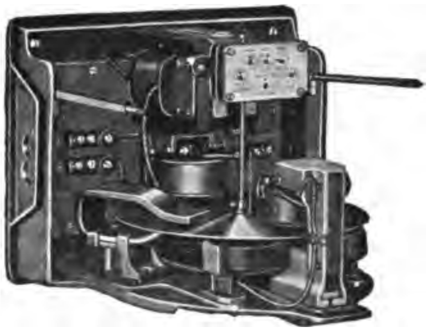

Fig. 15.

the same aluminum disc; the brake magnet acts also on the same disc and this makes the whole construction light and compact.

The method of connecting a polyphase meter into a three-phase circuit is shown in Fig. 16; the connections are based on the fact that each

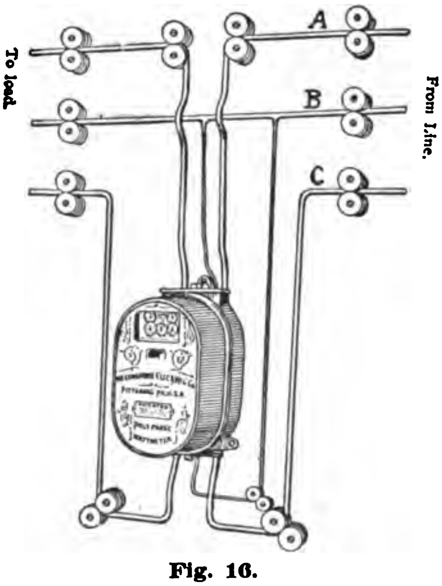

Fig. 16.

of the three line wires, for instance B can be considered as a common return wire for two other line wires A and C. Accordingly the scheme of Fig. 7 is used once for the wires A and B (three upper connections

to the meter) and then for the wires C and B (three lower connections). The three upper connections belong to the upper component meter, the three lower connections to the lower component. There are no electrical connections between these meters inside of the case.

The laboratory exercise with integrating wattmeters consists in adjusting and calibrating the meters and in studying the details of their construction. The calibration is done by comparing the meter to a good indicating wattmeter; it would take too long to keep the load on until the reading on the dial of the integrating wattmeter would change by an appreciable amount. Therefore the calibration is done by simply counting the number of revolutions of the armature shaft during a certain period of time (with a stop watch) and at a certain load as shown by the indicating wattmeter. The reduction ratio of the recording train is usually an even number, for example, 100, 200, etc., and knowing this ratio the wattmeter error can be easily calculated.

Suppose for instance, that a constant load of 1800 watts was put on an integrating wattmeter and kept constant by means of an indicating wattmeter. Let the time be measured during 15 revs. of the armature disc and found to be 28 secs; let the reduction ratio of the recording train gear be 1000 ÷ 1. If the value of one complete revolution of the pointer on the lowest dial is 1 kw-hr. (see Fig. 6*a*), the armature disk must complete one revolution while 1 ÷ 1000 kw hours or 1 watt hour is delivered to the load circuit. During the test the disk should have completed $1800 \div 3600 \times 28 = 14$ revs. In reality it made 15 revs; thus at this particular load the meter runs about 7.1% fast, and consequently registers 7.1% more energy than is actually consumed.

The students should calibrate in this way a commutator meter, an induction meter and a Sangamo meter. Begin with an overload of about 25% and gradually reduce the load to zero; when calibrating on alternating current it is necessary to take at least three separate curves: at non-inductive load, at a moderate load of constant power, but varying power factor, and at load of constant current value with again varying power factor. There are old meters on the market which register correctly at non-inductive loads only, and run too slow at inductive loads.

Before beginning the above calibration the students should investigate the action of friction compensating devices in the various meters, and the behavior at light loads of the meters not provided with such

compensation. The test consists in determining at what percent of full load the meter can be made to positively start without danger of "creeping" at no load. Also try to suddenly throw off a heavy load and see if the meter stops in a short time. Sometimes a meter correctly adjusted on a testing rack begins to creep when put on a wall where it is subjected to jarring from the street or from a nearby working engine. Try the effect of slightly jarring the meter under test and see what margin should be allowed for this effect. *Then before beginning the actual calibration adjust the meters so that they will read as accurately as possible on light loads.*

If time would permit it is interesting to calibrate one of the induction meters at various frequencies and with different wave form. Theoretically the calibration must differ under these circumstances, but it is claimed for good modern meters that they are "practically" accurate within wide limits of wave form and frequencies. It is not necessary to repeat the complete calibration curves; one or two points accurately observed should be sufficient for judging if the calibration remained the same.

A meter is better the higher its torque per unit of weight of the moving element, because the disturbing influence of the pivot friction is easier to overcome and the meter registers better at lighter loads. There is a special instrument on the market, the so-called torque balance by means of which the torque on the shaft of the meter can be directly measured in gram-centimeters, and two meters of different make compared.

Meters can also be compared in this respect by determining their friction-torque ratio. Adjust the friction compensator on no-load so that the meter is just balanced, i. e., so that it will creep under the slightest vibration. When this is done, apply load equivalent to the full capacity of the meter and take its speed under full load; then remove the friction compensator and note the difference in the speed of the meter under the same load. The percentage (decrease of speed) will be proportional to the friction-torque ratio; thus two per cent would mean 1:50; one per cent 1:100, etc. The higher the ratio, the better is the meter, at least as regards the disturbing influence of its friction.

In addition to the above tests it is recommended that the students carefully inspect the meters, having in view the points indicated in the

Appendix below, viz., as to a possibility of tampering with the meters for the purpose of defrauding the lighting companies.

In your report:

(a) Plot the calibration curves, preferably in per cent error, to per cent load or actual load abscissae.

(b) Give your results as to light load adjustment and creeping at no load,

(c) Give the results of the determination of the friction-torque ratio,

(d) Show the influence of wave form and frequency, if corresponding tests were made in the laboratory,

(e) Give your opinion as to the proper way of installing meters so as to minimize the possibility of the consumers tampering with them.

APPENDIX.

Report of the committee on "Theft of Current."

There is a tendency on the part of some electric light customers with low moral standards to defraud lighting companies by tampering with their meters and wires. A committee on "Theft of Current" was appointed by the National Electric Light Association to investigate the means most frequently used by offenders in this respect.

The following methods, as those most usually employed, were given in a report of this committee. It is desired that students understand these methods and precautions which should be taken in mounting and connecting meters and in their construction so as to make the below enumerated methods of tampering impossible or at least very difficult. This will prove useful in your future work with electrical operating or manufacturing companies.

1. Tapping the wires before they reach the meter, and connecting to them, in a more or less concealed manner, other wires whereby to draw off current.

2. Attaching wires, usually in a temporary manner, to the bare metal parts of the service switch or cut-out boxes.

3. After meter is removed, by connecting meter loops together.

4. Where customer pays a higher rate for light than for power, by tapping the power wires on the house side of meter for light.

5. Tampering with wires on the Edison three-wire system before they reach the meter, by disconnecting one of the outer wires at the service switch and connecting the same to the other outer wire, thereby throwing out all the lights on one side of the three-wire system, the meter registering the out-of-balance only.

6. Cutting or pulling out armature wire of meter, so that it will not make electrical connection. In several instances of this nature the armature wire was taped up at the original tap in such a manner as to conceal the opening.

7. Removing fuse from switch or cut-out, thus opening meter armature circuit.

8. Tampering with the meter in various ways, as follows:
   (a) Inserting wires or other articles under the case of the meter, so as to strike the disk and retard or stop it.
   (b) Drilling a hole in the meter case and inserting an article in a similar manner.
   (c) Inserting articles through screw holes of name-plate or meter case.
   (d) Forcing dust or dirt or insects, such as cockroaches, into the works.
   (e) Inserting short wires or iron filings into the meter, which cling to the magnets and by dragging in the disk retard its rotation.
   (f) Lowering jewel screws, so as to allow the disk to rest on magnets.
   (g) Breaking seals or seal wires of a meter, or pulling seal wires out of lead seal, so as to take off the meter case and gain access to the dials.
   (h) Breaking window protecting the dials, or removing glass by prying the glass guard open and slipping glass out.
   (i) Unscrewing the meter from the wall sufficiently to throw it out of level.

9. Where a customer has his own plant, causing the meter to run backward by charging the consumer's current through the meter into company's mains.

10. Bridging the meter in various ways, as follows:

(a) Putting a jumper on the wires, one end connecting to mains ahead of meter, the other to mains back of meter, or between meter and branch cut-outs.

(b) Temporarily connecting a wire from bare contacts of the knife service switch, to the bare contacts of the branch cut-out.

(c) Bridging the meter on the back of the meter board with a switch connection.

(d) Taking insulation off of leads running in and out of the meter to such an extent that the bare wires come in contact with the meter frame, or by placing a wire across the bare leads.

STUDY OF AMMETERS AND VOLTMETERS.

Ammeters and voltmeters are generally used in electrical testing and in commercial switchboard practice where it is necessary to measure electric currents and pressures. The instruments on the market vary widely in their accuracy, reliability, price, etc., and it is important for an electrical engineer to know the properties of different types of instruments, so as to be able to select in each case the proper one. This does not mean that the most accurate and expensive instruments should be selected in every case, but on the contrary, there are many cases where an inexpensive instrument will do just as well for all practical purposes. An intimate knowledge of the construction and consequently of the inherent limitations of various types of instruments on the market will enable the engineer to make in each case the most profitable investment.

A study of ammeters and voltmeters from this point of view is the purpose of this laboratory exercise. Moreover each type of instruments must be properly handled in order to give the best results, and it is expected that in this execise the students will learn the factors affecting the accuracy of various types of voltmeters and ammeters. Manufacturing electrical measuring instruments in itself is an important branch of electrical industry, and an opportunity is offered in this laboratory exercise for a study of materials used and the shape given to various parts, from the manufacturer's point of view.

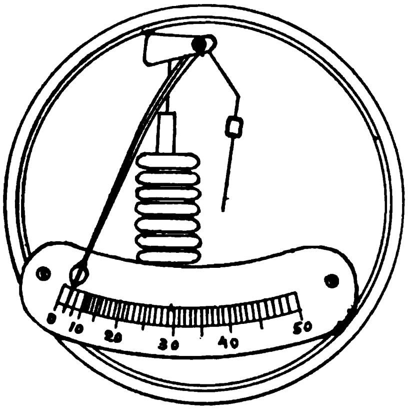

Fig. 1.

Ammeters and voltmeters used in electrical engineering practice can be first subdivided into two large classes: direct-current instruments and alternating-current instruments. The principal types of each class are as follows:

DIRECT-CURRENT INSTRUMENTS:

1. *Soft-iron instruments* which have a stationary coil and a piece of soft iron constituting the moving part (Fig. 1). Under the influence of the current flowing through the coil the iron becomes attracted to it and changes its position, moving in opposition to a spring or weight; this is indicated by the pointer on the scale. A great majority of instruments on the market, particularly of the cheaper kind are based on this principle, however different their form and the relative position of the coil and the moving iron. A very compact form is that of Thomson inclined coil ammeters (Fig. 2) in which the iron tends to move so as to place itself parallel to the lines of force produced by the coil.

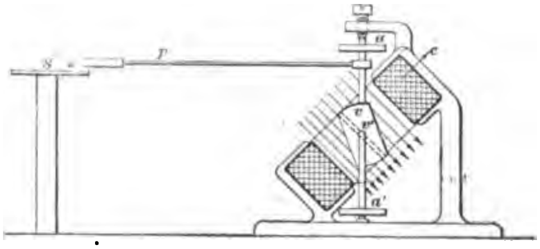

Fig. 2.

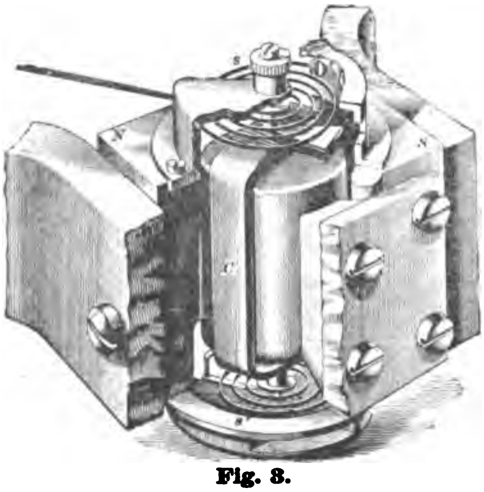

Fig. 3.

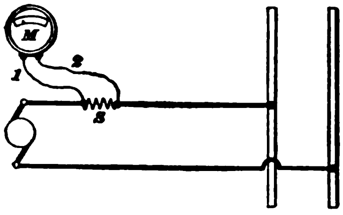

Fig. 4.

2. *Moving coil instruments* (Fig. 3). The current passes through a light moving coil C pivoted or suspended in the field of a stationary permanent magnet NS and deflected by its lines of force. The deflection is measured on the scale; the moving coil is returned to its zero position by two spiral springs s s^1, which at the same time serve for leading the current into the moving coil. Ammeters of this type are always provided with a shunt S (Fig. 4), through which the main current passes; the current in the moving coil is but a very small part of the current to be measured though it is strictly proportional to it. This is done because the moving coil must be very light and therefore wound of a small size wire, which could not carry any considerable current. Moreover, there would be a serious difficulty in leading a heavy curent in and out of the coil.

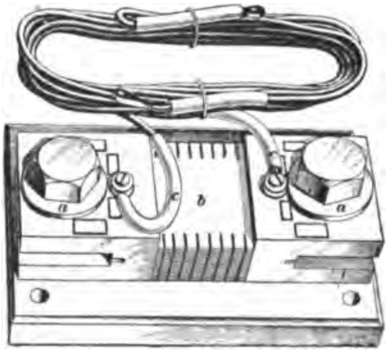

Fig. 4a.

An ammeter shunt for heavy currents is shown separately in Fig. 4*a*. Its main part *b* is usually made out of ***manganin*** or some other material having a low temperature coefficient. The shunt is provided with two heavy terminals *a a* for the main current, and two small terminals to which ammeter leads *c c* are connected. The shunt is sometimes placed inside of the instrument, but for heavy currents, outside. Beginners sometimes forget to use the shunt and connect the moving coil directly into the circuit. This invariably results in either the moving coil or the spiral springs being burned up, or at least the pointer bent or broken.

The moving-coil ammeters are in reality low reading voltmeters which measure the difference of potential at the terminals of the shunt. The resistance of the shunt being constant, the difference of potential is evidently proportional to the current flowing through it. Thus the same moving-coil instrument can be used throughout any range of currents by providing a suitable set of shunts. Sometimes instead of calibrating the instrument directly in amperes it is calibrated in actual volts (usually millivolts), and is called a millivoltmeter. Then if the resistance of the shunt is known amperes can be easily calculated. The advantage of such an arrangement is that the same millivoltmeter can be used with any shunts.

Moving-coil voltmeters are always provided with a high resistance in series. This resistance or multiplier *R* (Fig. 5) is placed inside or outside of the instrument *V* as the case may be. In the latter case the person using the instrument must not forget to connect it into the circuit; otherwise the voltmeter will surely be burned out. The range of the voltmeter can be varied at will by changing the resistance of the multiplier, and most of the voltmeters used for all around testing purposes are provided with several multipliers. This applies not only to moving coil instruments, but to all other types of voltmeters as well.

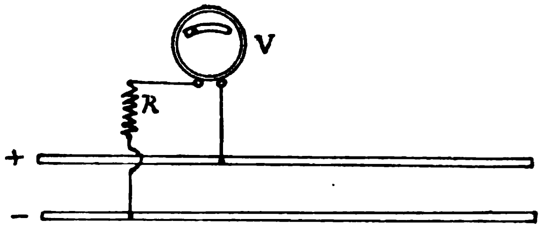

Fig 5.

Moving-coil instruments are undoubtedly the most accurate and sensitive for direct-current work, though they are more expensive than soft iron instruments, and also are more easily damaged by overloads and rough handling.

3. *Electro-dynamometer type instruments* (Fig. 6). Ammeters of this type have a stationary and a moving coil connected in series and placed normally at right angles to each other. When a current passes through them, the movable coil tends to place itself in a plane parallel to that of the stationary coil, and the deflection is shown on the scale.

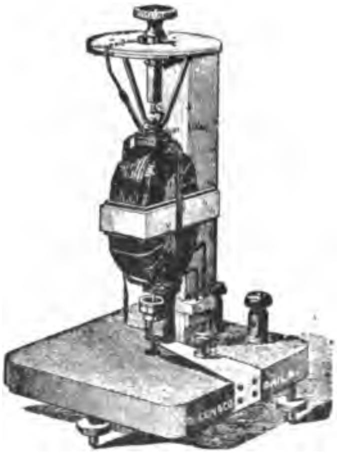

Fig. 6.

Spiral springs are used for returning the coil in zero position, and also as a resisting force.

Instruments of this type are adapted for voltmeters (Fig. 6*a*) better than for ammeters, since in the latter case it is difficult to devise a satisfactory arrangement for leading heavy currents into the moving coil, without interfering with its free motion. Electro-dynamometer type instruments are seldom used for direct-current measurements in view of the existence of moving-coil instruments, but they are one of the most satisfactory types for alternating current work.

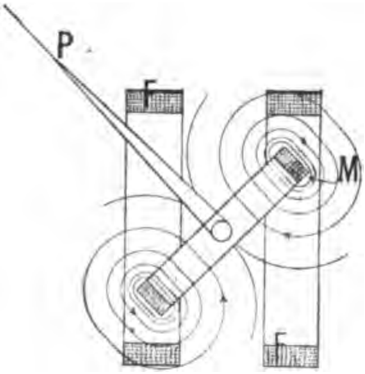

Fig. 6a.

4. *Hot wire instruments* (Fig. 7), based on the expansion of a wire heated by the current to be measured. In these instruments the pointer is subjected to two forces: a spring tends to deflect it from zero position to the opposite end of the scale, but is prevented by a tightly stretched special alloy wire (platinum silver) also acting through a mechanical transmission on the same pointer. When the current is flowing through this wire it raises its temperature, and the wire slackens somewhat allowing the spring to deflect the pointer. The heavier the current the looser becomes the wire and the larger is the deflection on the scale. The instrument is calibrated as all other instruments by comparison with some standard device (for instance a standard cell in connection with a potentiomometer and a standard shunt). Ammeters of this type in common with moving-coil instruments are provided with shunts, except in smaller sizes (below 5 amps.), where the total current to be measured is made to flow through the instrument. Hot-wire instruments are usually used for alternating current work.

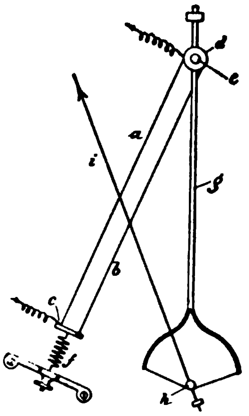

Fig. 7.

The particular instrument shown in Fig. 7 has the following construction: a wire, *a-b,* of high resistance, low temperature co-efficient and non-oxidizable metal, is secured at one end to a plate, *c,* passed around a pulley, *d* secured to a shaft *e* and its free end brought back again and mechanically though not electrically attached to the same plate *c.* Plate *c* is kept under stress by the spring *f,* which constantly tends to pull it in a direction at right angles with the axis of the shaft *e,* and is so

guided that it can be moved in that one direction only. To the shaft *e* is likewise secured an arm *g*, bi-furcated at one end and counterweighted at the other. Between the extremities of the bi-furcated ends of the arm *g* is another shaft *h*, on which there is a small pulley and to which is attached the needle *i* that gives the desired indications; a fine silk fiber is attached at one end to one of the arms of *g*, then passes around the pulley and the staff *h* and finally has its other extremity secured to the other arm. The arms are springy and serve to keep the silk fibre taut. The current to be measured flows through the wire *a* only, entering and leaving as indicated by the arrows.

Evidently, when *a* is heated by the passage of current, it expands, and this, as *a* and *b* were originally under the same tension, makes *a*'s tension relatively less than that of *b*, and the equilibrium can be restored only when the pulley *d* rotates sufficiently to again equalize the strain. The rotation of *d*, of course, carries *g* with it and *g* in moving, causes the silk fibre to rotate the shaft which carries the needle. If the temperature of the air surrounding the instrument changes, *a* and *b* are affected alike and their resulting equal expansion simply results in a movement of the plate *c* back or forth in its path without any tendency to rotate the pulley.

5. *Electrostatic instruments* (voltmeters only). These instruments are not so much used as other types, except in special research work. They are well adapted for measuring high voltages, since they do not require any expensive multipliers, and also in cases where the currents to be measured are so small that even the small current taken by the ordinary voltmeter would affect the results.

Electrostatic voltmeters utilize, as a motive force, the attraction between two plates charged electrically. One of the plates is stationary (Fig. 8), the other movable, and the deflection of the movable plate is shown on the scale. When the voltages to be measured are comparatively low, plates of a considerable area are required in order to obtain an appreciable force of attraction. In this case several plates are used, as shown in Fig. 8*a* (multicellular voltmeter).

Alternating-current instruments:

1. Soft-iron instruments mentioned before are also extensively used for measuring A. C. currents and voltages; their calibration is, however, not quite the same in both cases, and also depends somewhat on the fre-

quency of alternating currents; this is due to the influence of hysteresis and eddy currents in the moving iron. In designing an alternating-current instrument of this kind care should be taken to use as little iron as possible, to have it thoroughly subdivided and also to avoid eddy currents in other metal parts of the instrument.

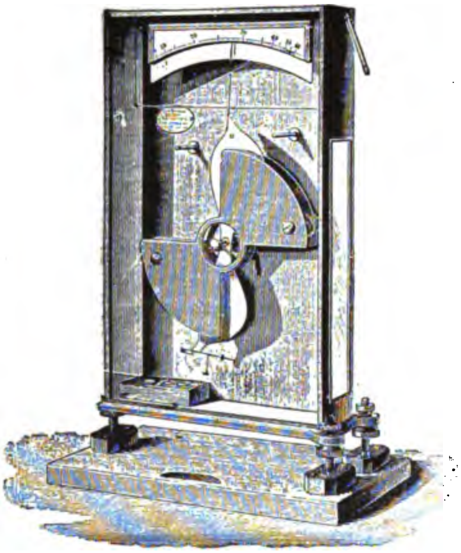

Fig. 8.

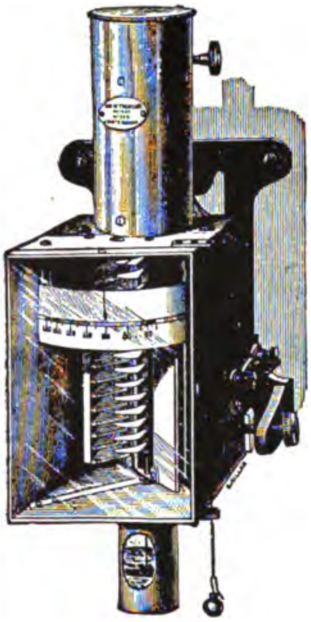

Fig. 8a.

2. It is evident that moving-coil instruments cannot be used for measuring alternating currents, since the deflection of the coil depends on the direction of the current, and when the current changes its direction many times a second the coil simply remains on zero. Moving coil instruments are the only ones of the above described five types of direct-current ammeters and voltmeters, which cannot be used on A. C. circuits, for the reason that permanent magnets are used in these instruments and therefore the deflection must depend on the direction of the current. Moreover, moving coil instruments are the only ones in practical use which show the polarity or the direction of the current.(*)

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* Some galvanometers used in physical research have stationary coils and moving steel magnets; such instruments also show the polarity or the direction of the current; they are, however, not used at the pr sent time as voltmeters and ammeters, in commercial work.

3. Electro-dynamometer type instruments are widely used in alternating current testing both as voltmeters and as ammeters. Voltmeters of this type are more convenient for use, since they can be made direct-reading and portable. Their moving part is very similar to that shown in Fig. 3; the stationary part F (Fig. 6*a*) consists of similar coils instead of a magnet. The ammeters or as they are usually called electro-dynamometers (Fig. 6) are not so convenient, since mercury cups must be used for connecting the moving coil into the circuit. Moreover, they are not direct-reading, but have a torsion head, by means of which the electric attraction is compensated. It is expected that the students, after having inspected an instrument of this type in the laboratories, will make clear to themselves the difficulties in making a convenient portable and direct-reading ammeter based on the attraction of a moving and a stationary coil.

Electro-dynamometer type instruments show true *effective* values of alternating currents and voltages, because the attraction between two coils is proportional to the squares of the instantaneous values of the current flowing through the coils. They can be calibrated by direct current and used on alternating currents. This is a great advantage of this type of instruments.

4. Hot-wire instruments are also used to a considerable extent for alternating-current testing. The heat developed in the wire being proportional to the square of the instantaneous values of the current these instruments also indicate the true effective values of alternating currents and voltages, and like dynamometer type instruments can be calibrated by being compared to accurate direct-current standards. A weak point of hot-wire instruments is that the hot wire is easily burned out by overloading the instrument, thus acting itself as a fuse. This point must be kept in mind when using hot-wire instruments.

5. Electrostatic voltmeters can be conveniently used on high-tension

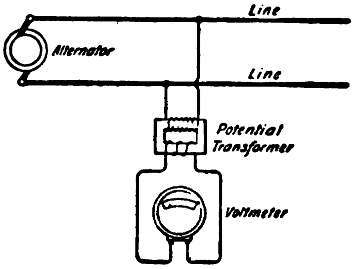

Fig. 9.

A. C. circuits; they are also used as ground detectors. Usually, however, it is preferred to measure high voltages by using voltage reducing or potential transformers of a known ratio (Fig. 9). Then an ordinary alternating-current voltmeter of either of the above types can be connected to the low-tension side of the transformer, and the voltage measured without any danger to the operator.

6. There is a particular type of instrument used to a considerable extent on alternating-current switchboards, namely, ***induction type instruments*** (Fig. 10). The current to be measured flows through the coil *C* of the laminated iron core *I* and produces in it a pulsating magnetic field. A pivoted aluminum disc D is subjected to the inductive action of this field in the air gap of the core, and can be made to move under the influence of eddy currents induced in it, if these currents can be made *unsymmetrical* in respect to the iron core. This is obtained by placing an electric screen or a secondary coil *S* on *one side* of the iron core. The currents induced in this screening coil oppose the primary currents and thus weaken the magnetic flux on one side of the core, and also change its phase. This combination of the two fluxes produces unsymmetrical currents in the aluminum disc and it moves, thus producing a deflection on the scale B. In short, this instrument is a single-phase induction motor, the screening coil taking the place of a split-phase arrangement. The instruments based on this principle are robust, convenient for use, and possess a fair degree of accuracy. Of course they can be used on alternating currents only, and their indications depend to a considerable degree on the frequency of the supply. Commercial ammeters based on

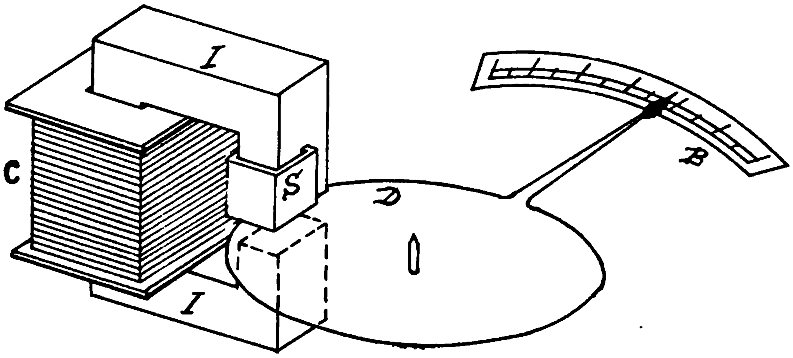

Fig. 10.

this principle are mostly wound for 5 amps., and adapted for use in connection with series or current transformers (Fig. 11), by means of which currents of any desired range can be measured with the same instrument. Volmeters of this type are provided with multipliers and for higher voltages also with shunt transformers.

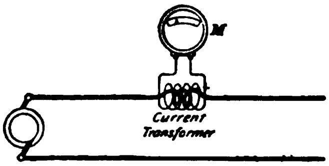

Fig. 11.

Thus, summing up the conditions under which the above types of voltmeters and ammeters are used in practical engineering work, we have: soft iron instruments which are the cheapest and are used for both D. C. and A. C. where no particular accuracy is required; for accurate D. C. work moving-coil instruments are employed exclusively, while electro-dynamometer type and hot-wire instruments are used for accurate A. C. measurements. Recently, portable induction-type instruments are being introduced for this purpose, though so far they have been mostly used for A. C. switch-board work. Electrostatic voltmeters are used to some extent for high-tension measurements, and for some classes of special work.

The principal requirements for a good measuring instrument are:

1. Permanency of calibration;
2. Insensibility to stray magnetic fields;
3. "Dead beat" quality, i. e., the instrument should not swing too long before giving a definite indication.

All these requirements can be met and are met to a larger or smaller degree in modern measuring instruments; however, the more strict the requirements, the more expensive becomes the instrument, and it is therefore advisable not to go further in the demand for accuracy than the case may require.

1. The calibration may be affected by a change of form or relative position of parts inside of the instrument, by an increased friction in pivots, aging of springs or iron, and in instruments with permanent magnets, by the same losing part of their magnetism.

2. Some of the above-mentioned types of instruments are inherently less affected by external stray fields than others, and all of them can be sufficiently protected by enclosing them in a cast iron case. Hot-wire instruments are practically unaffected by stray fields, since their action is not based on a magnetic effect; induction instruments are affected very little since their air gap is small and their own field quite strong. Electro-magnetic instruments are affected the most, and should never be placed near dynamos or on a switchboard within a loop of bus bars and cables carrying strong currents. Electro-dynamometer type instruments are affected by the terrestrial magnetism when used on direct current; therefore in accurate measurements it is essential to reverse the current in the instrument and to take the average of two readings.

3. The "dead beat" quality is always desirable in an instrument, though usually it can be attained only by the addition of an extra damping device. An aluminum vane is quite frequently used for this purpose, the damping being attained either by the resistance of the air to the movement of the vane or by placing this vane between the poles of a permanent magnet, so as to induce in it eddy currents. Moving-coil instruments are easily made "dead beat" by making the frame of the moving coil of aluminum. The currents induced in it by the permanent magnet are sufficient to make the instrument dead beat (the word "aperiodic" is sometimes used instead of the expression "dead beat.")

It will be noticed that different types of instruments have a somewhat different character of scale. Thus the scale of moving-coil instruments is usually perfectly regular, all divisions from zero to full scale being equal. On the other hand, hot-wire instruments have a very irregular scale, divisions being crowded on the lower part of the scale, so that the instrument can be read with fair accuracy on not less than 40 per cent of its full range. Some dynamometer-type instruments have larger divisions in the middle part of the scale, and smaller ones on both ends. Sometimes a scale is made suppressed on its lower part on purpose, in order to make larger the division in the useful range of the instrument. In instruments based on the hot-wire or dynamometer principle, the scale is, of necessity, irregular, since the deflecting force in such instruments is proportional to the square of the current, instead of being directly proportional to the current; the scale of moving coil instruments can be made fairly regular. However, *a regular scale is by no means always desirable in switchboard service,* though it is very con-

venient for testing and experimental purposes, since it increases the useful range of the instrument.

As was stated above the purpose of this exercise is to give the students an opportunity to see the construction of ammeters and voltmeters and to observe the good points and the limitations of the different types of instruments. This should enable them to properly handle instruments and to intelligently select the proper instruments for a given case.

The instrument to be investigated must be connected into the circuit, and if necessary another instrument used as a standard must be also connected into the same circuit, in order to observe the comparative behavior of both instruments. There are many points in regard to which two instruments of the same range and of different type can be compared to each other; the following are among the most important:

(1) Are there any defects in the construction that give indications that the instrument cannot have a permanent calibration?

(2) Is the instrument "dead beat," and if not how can it be made dead beat in the most convenient way? The degree of being "dead beat" can be measured by suddenly closing the circuit on a current or voltage that gives a certain per cent of full scale deflection, say 60 or 70% and observing the time which it takes for the pointer to become steady at this point. This method of defining the "dead-beat" degree is entirely arbitrary, but if the same procedure is used on all the instruments under test, the results will permit the comparison of the instruments in this respect.

(3) If the instrument is absolutely dead-beat (aperiodic) note how long it takes the pointer to assume its final deflection. Also see if the moving part is capable of following more or less rapid fluctuation of current or voltage. This point is particularly important in hot-wire instruments, since they are somewhat sluggish on fluctuating loads; it takes a certain amount of time for a wire to change its temperature and therefore its length. Determine this sluggishness numerically, by varying the current periodically at a certain speed and by a certain percentage, and observe the behavior of the instrument under test, as compared to that of the standard instrument.

(4) See if the pointer always returns to zero or at least to the same point when the circuit is opened; if not what is the cause. In hot-

wire instruments a special screw, accessible from the outside, is provided for setting the pointer at zero.

(5) Can the instrument be used indifferently in a vertical and horizontal position? Is the moving part sufficiently well balanced so that small differences in the position of the instrument do not affect the calibration?

(6) What kind of force is used to deflect the pointer from zero position, and what is the resisting force?

(7) How to explain the character of the scale (regular, crowded on one side, etc.) by the character of the moving and resisting forces. What changes should be made in the instrument to get a scale more regular, or still more suppressed on one side?

(8) Is the instrument conspicuously bulky and heavy as a result of a particular construction adopted; what are the principal materials used and what are in your opinion the most important and expensive operations in manufacturing the instrument?

(9) Is the calibration affected by the temperature, and if so how much? Is there any compensation in the instrument for the influence of temperature and if so of what does it consist? Some alternating current voltmeters have a small thermometer on the face of the instrument and an adjustable rheostat in series with the multiplier. Some hot-wire instruments have the plate on which the wire is stretched made of a material having the same expansion coefficient as the wire itself; in this way no stresses are produced in the wire by changes in temperature of the surrounding air.

(10) If the instrument has an external shunt determine if the shunt has a negligeable temperature coefficient, or if the calibration of the instrument changes because of the heating of the shunt.

(11) Determine in how far the instrument is affected by stray magnetic fields and a proximity of large iron masses. Does the iron case of the instrument shield it entirely from these influences, and does not it introduce an error by itself?

(12) Is the instrument influenced by terrestrial magnetism and is there any means to eliminate this influence, for instance by reversing the current and taking an average of the two readings? Is there any position of the instrument with respect to the meridian, such that the above influence becomes a minimum?

(13) Does the instrument show an appreciable hysteresis effect,

so that indications on increasing and decreasing currents are different?

(14) Is the calibration the same on D. C. as on A. C. and if not determine the difference and explain the cause?

(15) Is the calibration affected by the wave form of alternating current?

(16) What is the energy of consumption in the instrument itself and how does it compare with that of other instruments having the same range?

Arrange your laboratory work with ammeters and voltmeters having in view the above enumerated 16 points. Describe in the report the general arrangement of the test, the construction of the instruments used and give the calibration curves. Also answer for each instrument studied the above asked 16 questions. Do not repeat the questions; simply refer to them by number.

In this exercise as in all other laboratory tests is it not expected that the students should at once become experts on the question studied. It is only hoped that they will get the underlying principles and acquire some skill in handling the apparatus; the rest will come with time.

NOTE—For general testing purposes it is very convenient to have a portable volt-ammeter set, as one shown in Fig. 12. The

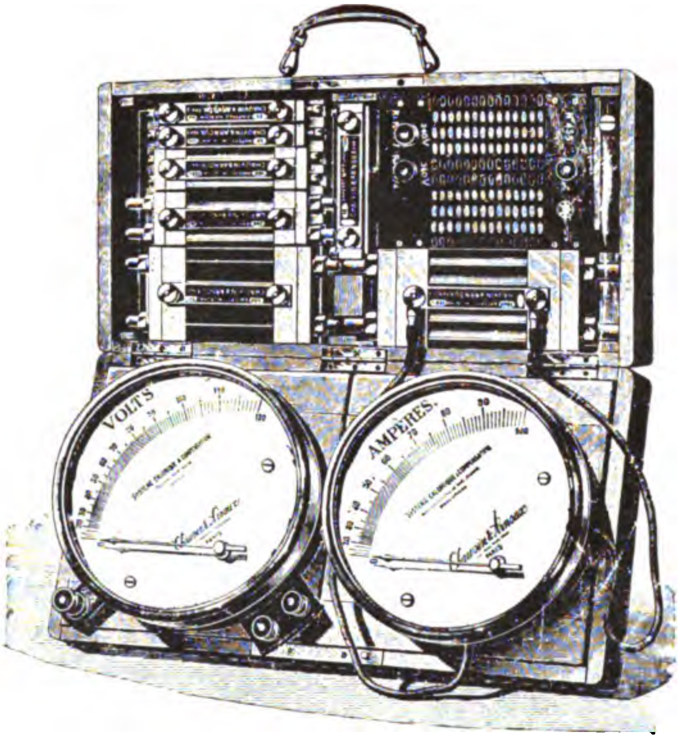

Fig. 12.

ammeter of this particular set is provided with six different shunts covering the range from 25 to 1000 amp.; the voltmeter is provided with two multipliers by means of which its original range can be increased twice or four times. Of course, it is not necessary to have this same range in all cases; in each case the shunts and the multipliers must be selected so that the set would cover as much as possible the total range of the work for which it is intended to be used.

SAFETY OF ELECTRICAL PLANTS.

Electrical machinery and wiring if improperly or carelessly installed, may become a source of annoyance, fire hazard, and danger to life. In order to minimize a chance of such disturbances and make electric installations reliable and safe, a code of rules and regulations was drawn up in 1897 by the united efforts of fire insurance companies and various engineering and business associations interested in the development of electrical industry. These rules, commonly known as the "National Electric Code" or as Fire Underwriters' Rules are at present recommended and adopted by the following associations:

American Institute of Architects.
American Institute of Electrical Engineers.
American Society of Mechanical Engineers.
American Institute of Mining Engineers.
American Street Railway Association.
Associated Factory Mutual Fire Ins. Co's.
Association of Edison Illuminating Companies.
International Association of Fire Engineers.
International Association of Municipal Electricians.
National Board of Fire Underwriters.
National Electric Light Association.
National Electrical Contractors' Association.
Underwriters' National Electric Association.

The rules are being yearly revised by the delegates of these associations so as to be up to date with the progress of the art. They are published in book form and can also be found reprinted in various pocket-books and text books (see for instance Foster's pocket book, p. 762). A very convenient edition with explanatory notes and examples is that of the Associated Mutual Fire Insurance Companies.

It must be understood that these rules have no legal power, as the corresponding rules in some other countries have, but being adopted by all the insurance, electrical, mechanical, architectural and allied interests of the country, their authority is acknowldgeed by all reliable manufacturers, contractors and consulting engineers, and they strictly adhere to

them in their business. Moreover it is difficult at present to insure a building unless its electrical installation is put up in accordance with these or similar rules.

In view of the importance of the National Electrical Code, it is absolutely necessary for every electrical engineer to become familiar at least with the general arrangement of the rules and their principal requirements. The simplest way to begin this work is to go over an electrical installation with the Underwriters' rules in hand, and to compare different parts of the installation with their requirements, as though assuming the duties of a fire insurance inspector.

The general plan of the National Electrical Code is as follows:

CLASS A.—STATIONS AND DYNAMO ROOMS. Includes Central Stations; Dynamo, Motor and Storage-Battery Rooms; Transformer Substations, etc. Rules 1 to 11.

CLASS B.—OUTSIDE WORK, all systems and voltages. Rules 12 to 13A.

CLASS C.—INSIDE WORK:—

General Rules, all systems and voltages. Rules 14 to 17.

Constant-Current Systems. Rules 18 to 20.

Constant-Potential Systems:—

General Rules, all voltages. Rules 21 to 23.

Low-Potential Systems, 550 volts or less. Rules 24 to 34.

High-Potential Systems, 550 to 3500 voles. Rules 35 to 37.

Extra-High-Potential Systems, over 3500 volts. Rules 38 and 39.

CLASS D.—FITTINGS, MATERIALS AND, DETAILS OF CONSTRUCTION, all systems and voltages. Rules 40 to 63.

CLASS E.—MISCELLANEOUS. Rules 64 to 67.

CLASS F.—MARINE WORK. Rules 68 to 83.

With the exception of Classes E and F, which are of less importance for general work, the rest of the rules can be subdivided in two large classes: 1, *installations* (classes A. B and C), and *fittings and supplies* (class D). In the latter class rules will be found prescribing details of construction of switches, fuses, lamp sockets, wire, etc. The former class contains regulations as to how these supplies must be installed and which types are permitted in various cases.

In accordance with this subdivision of the rules the laboratory exercise is also divided into two parts: inspection of supplies and inspection of installations.

1. Inspection of supplies.

This work is covered by the Class D of the National Electrical Code. The following are the supplies used mostly in installations, and on the quality of which the safety and the reliability of service essentially depends: insulated wire and cable, conduits, cleats (for supporting wire), switches, cut-outs and fuses, cut-out cabinets, rosettes and lamp sockets. Samples of these supplies are provided in the laboratory and the students are to inspect as many of them as time will permit. The inspection consists in taking a device apart or at least opening it if necessary, and in comparing the details of its construction and the materials used with those specified in the corresponding section of the Underwriters' rules.

If the device only partly satisfies these rules, state which rule is not complied with and suggest the changes necessary to be made in order to make it "approved." Suppose, for instance that you have to decide about a switch; you will find in the Code rule 51 relating to switches. Sections *a* and *b* of this rule refer to *all* types of switches, and you must first see if your switch satisfies the conditions specified there. Then if it is a knife switch, you will find the requirements specified under sections *c* to *k*; if it is a snap switch the rules *l* to *t* apply to it. *For knife* switches you will find that they must be mounted on non-combustible bases, that the hinges must be provided with spring washers in order to insure good contact, that the separation between the parts of opposite polarity must be not less than a certain limit, etc. See if all of these requirements are fulfilled in the switch under inspection and if not, state whether in your opinion the switch should be absolutely condemned, or if it could be used after certain changes.

A "List of Approved Electrical Fittings" is published semi-annually by the Fire Underwriters, as a supplement to the National Electrical Code. It contains the names of firms, trade marks and types and styles of fittings manufactured in accordance with the Fire Underwriters' rules. When purchasing or specifying any of such supplies it is not necessary to compare them with the National Electrical Code, because they are manufactured in accordance with the requirements of this code.

In your report on inspection of supplies state your findings, referring to the rules by number (for instance 51*m*) and give a few free-hand sketches suggesting some changes in the devices inspected in the laboratory.

2. *Inspection of installations.*

This work should be done following the three first classes of rules of the National Electrical Code:

A. Stations and Dynamo Rooms.

B. Outside work.

C. Inside wiring.

The work consists in inspecting the wiring and the machinery installed in various places on the Campus and in comparing it to the requirements of the Fire Underwriters.

In addition to the laboratory installations proper, electrical wiring in various University buildings is availble for inspection, and also the University power house in the Gorge, motors in the shops, etc. In order that the students may intelligently follow up the connections a short sketch of the power distribution on the Campus in given below.

Electric power is generated in the power house in the Gorge in the form of three-phase 2200v. 60-cycle current by two water-wheel driven alternators. It is distributed throughout the Campus, partly overhead and partly by underground cables. Separate buildings are provided with transformers, in which the voltage is stepped down to 110v. or 220v. for lighting and motors.

Induction motors used in Sibley laboratories and shops are supplied with 220 v. three-phase current from the transformer house situated in the court between Sibley and Mechanical Laboratory buildings. Incandescent lighting for these buildings is supplied from a 110v. transformer installed in a pit in the locker room under Sibley Dome.

Before this system was completed several 500v. direct-current motors were in operation on the Campus, and in order to be able still to to use them, a motor generator set is installed in the power house converting the 2200v. three-phase current into 500v. direct-current, which is then distributed throughout the Campus.

In addition to these two sources of current a limited amount of 110v. direct current is available from one of the exciters of the large alternators. This power is chiefly used for projection lanterns, and for charging small storage batteries, etc.

In the electrical laboratory itself, alternating currents at 220 and 110 v. are available from the Sibley transformers, and also 2200v. from the high-tension line. 500v. and 110v. direct current supply from the power house is also available, and in addition to these, direct current at

110v. is generated in the laboratory for work where the voltage must be kept more nearly constant than is possible in the power house, in the Gorge. For 220v. direct-current motors a booster set is used, raising the laboratory voltage from 110v. to 220v.

With this information about the sources of power the students will have no difficulty in tracing out the connections during their inspection of the wiring.

It is desired that the students inspect the following installations:

(1) Generators in the laboratory and in the power house (rule 1.)

(2) Switchboard in the laboratory and in the power house (rule 3.)

(3) A few motors in the shops, and large fan motors in the University library (rule 8.)

(4) Outside wiring (rules 12*a-h*.)

(5) Inside work (rules 14, 16, 17, 21, 23, 24-28.)

As this work of inspection does not require the use of any apparatus or current, part of the inspection can be done outside of the regular laboratory time. It is most earnestly recommended that the students spend as much time as possible in inspecting the University installations, with the National Electrical Code in hand. This will give them one of the most valuable experiences, which no books can give and which will enable them to distinguish good workmanship from a "cheap job."

In the report on this work state what machines and wiring you inspected, and which rules you found to be complied with. Where you think the installation is not in accordance with the National Electrical Code, state so referring to the rule number, and also give suggestions as to what changes should be made.

During the inspection of the wiring be sure that you do not come in contact with live high-tension wires; also do not use screwdrivers, etc., which may cause a short-circuit. Above all do not open or close any switches without permission from an authorized person.

NOTE. The following suggestion may help you in your future practice: In all contracts for electrical work introduce a clause to the effect that all work must be done strictly in accordance with National Electrical Code, and that no fittings should be used which are not found in the latest edition of the "List of Approved Fittings." This clause will insure you good work and materials, and in case of a litigation you will have the support of the competent and impartial National Board of Fire Underwriters.

TRANSFORMER TEST.

The purpose of this laboratory exercise is to illustrate the action of transformers and to indicate the principal commercial tests performed on them. As you already know, a transformer consists of two windings placed on a common iron core and connected respectively to the source of power and to the power consuming apparatus (Fig. 1). The voltage of the supply is by the use of a transformer increased or reduced very nearly as the ratio of the number of turns in the coils.

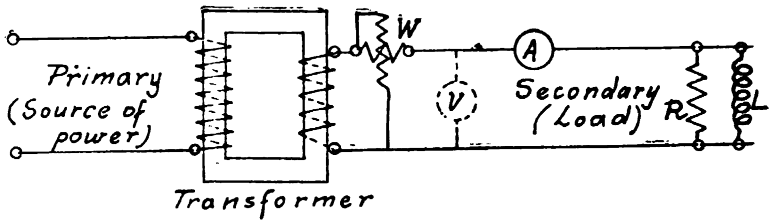

Fig. 1.

The principal requirements for a good transformer are:

(1) It must possess a good inherent regulation, in other words the voltage drop inside of the transformer itself must be small;

(2) Its efficiency must be high;

(3) It must be so proportioned as not to get too hot in continuous operation.

The fundamental property of the transformer is that the currents primary and secondary are very nearly as the inverse ratio of the corresponding voltages.

This can be explained in two different ways: in the first place, as the losses in the transformer hardly amount to a few per cent of its full rated capacity, practically all of the energy supplied to the primary is delivered to the secondary, and as this energy is measured by the product volts × amperes, we have, to a very close approximation:

$$E_1 I_1 = E_2 I_2,$$

or

$$\frac{I_1}{I_2} = \frac{E_2}{E_1}\,.$$

Another explanation is based on the fact, that it takes but a very small current to magnetize the transformer iron (closed magnetic circuit, low flux density); therefore the secondary number of ampere-turns is practically equal to the opposing primary number of ampere turns, or

$$I_1 n_1 = I_2 n_2.$$

But in transformer, as in any other apparatus based on induction, voltages are proportional to the number of turns, and it follows again that

$$\frac{I_1}{I_2} = \frac{n_2}{n_1} = \frac{E_2}{E_1}.$$

Before describing the experiments proper, a few general remarks may be useful in regard to the three above mentioned points: regulation, efficiency and temperature rise.

(1) The question of regulation has a great practical importance, particularly for lighting transformers, where a difference of even two per cent between the no-load and the full-load voltage is quite appreciable for incandescent lamps. For transformers used on power circuits this is not so important, except where incandescent lamps are connected to the same circuit. In this case the requirements for regulation must be very strict because the inherent regulation of a transformer on inductive loads is naturally worse than on non-inductive load.

The regulation of a transformer can be determined either directly, by actually loading the transformer, or indirectly by calculation. The indirect method though more convenient in practice, especially with large transformers, presupposes a more thorough knowledge of the theory than can be expected at this point. For this reason and also in order to give the students an opportunity to see the transformer in actual operation, the regulation is to be determined in this exercise by direct loading of the transformer on ohmic and inductive resistances. During this test the above explained property of the transformer that the currents are as the inverse ratio of the voltages can also be verified experimentally.

In doing so you will notice that on very light loads the primary current does not increase quite proportionately to the secondary current, because of the extra magnetizing component of the primary current. But beginning say at ¼ load and even less this component is already negligeable as compared to the value of the total current, and the currents can be assumed as proportional to each other.

(2) The question of efficiency is important from several stand-

points: the efficiency of good modern transformers is so high (from 95% up to 98%, according to the size) that any lower figure surely shows a defect in design, workmanship or materials, and such a transformer should not be accepted. Besides, transformers are connected to the city mains all the time and run continually on full iron loss, which the lighting company has to supply and for which it is not paid. Remembering that thousands of small transformers are connected to one power station, this item becomes quite appreciable. Moreover, all the losses in a transformer occur in the form of heat and have to be radiated under very unfavorable conditions; the lower these losses are the cooler the transformer is in operation, the safer its insulation and the more easily it can stand accidental overloads.

The most natural way of measuring the efficiency of a transformer would be to have it actually loaded and have one wattmeter in the primary and another in the secondary circuit. In this way the input and the output could be read directly and their ratio would give the efficiency. However, this direct method has serious drawbacks, and is hardly ever used. It involves the use of a wattmeter on the high tension side; it requires an utmost accuracy of calibration of the wattmeters because the difference in the readings is but a few per cent; moreover, with large transformers the amount of power required for full-load test is not always available. Therefore it is customary to measure the losses separately (at no load) and then to *calculate* the efficiency of the transformer: this can be done with much simpler means and a considerably greater accuracy than is possible with the direct method.

(3) Safety of operation of a transformer depends essentially on the maximum temperature which it attains under load. An insulation which is perfectly safe and can even stand a considerable over-potential at ordinary temperatures, easily breaks down when subjected to a sufficiently high temperature; transformer iron undergoes so-called "ageing" under the influence of heat, that is to say, its properties change so that its hysteresis loss increases considerably. This in turn increases the temperature of the transformer. Therefore a test on temperature rise under actual load conditions becomes one of the most important practical transformer tests.

A transformer heats up in operation because of its core loss and the I^2R loss in its windings. Core loss depends on the flux in the iron, or, which is the same, on the applied voltage, and is practically inde-

pendent of the load; copper loss is directly proportional to the square of the current flowing through the windings. Therefore in order to test temperature rise in a transformer it must be subjected to its full rated voltage and full load current.

Such a test offers no difficulties with small lighting transformers, which can be easily loaded on lamp rheostats, etc.; but with large high-tension transformers such a load test becomes not only very difficult and expensive, but in many cases impossible. In such cases when two similar transformers are available one transformer can be loaded on the other, and this latter connected back to the source of supply, so that no power is wasted except that necessary for supplying the losses in both transformers. This method, the so-called "pumping back" or "stray power" method, is often used not only in application to transformers but to generators and motors as well.

When but one transformer is available its windings can be heated artificially by direct current, while total iron loss can be produced by applying the full rated A. C. voltage at the corresponding terminals. Thus it will be seen that the complete transformer test as described above comprises:

(a) Loading the transformer;
(b) Measuring the losses;
(c) Heat run or temperature run.

These three tests shall now be described more in detail.

1. *Loading Transformer.*

The transformer provided for this test is an ordinary lighting transformer such as is used in cities for stepping the 2200v. supply down to 110 v. or 220 v. to be used in houses for light and power. If the distributing network is laid underground (cables) such transformers are usually placed in the basements of the houses; if the distribution is done by means of overhead wires the transformers are mounted on the outside of one of the walls or on a pole near the house.

The transformer which we have in the laboratory is mounted on a pole to represent this latter case. An ammeter and a voltmeter are provided on both low and high tension sides (Fig. 1) and in addition a wattmeter is connected on the low tension side, to be used on inductive loads. First determine the regulation at non-inductive load. The primary volts must be kept constant; the secondary voltage will then decrease as the load increases. If it should be impossible to keep the primary volts

absolutely constant, the secondary volts must be corrected before plotting the curves; within the limits of fluctuations it can be safely assumed that the secondary voltage is directly proportional to the primary, so that if, for instance, the primary voltage was 2% low when a reading was taken, the observed secondary voltage must be also increased 2% before plotting the regulation curve.

After this test the regulation of the transformer must be investigated on inductive loads. With non-inductive load there is but one quantity to be varied, viz., amperes (or, which is the same, watts); on inductive loads there are three variables; amperes, watts and power factor. Any two of these can be taken as independent, and curves plotted giving the regulation of the transformer say for constant watts, constant current or a constant value of the power factor. It is much easier to regulate the inductive and non-inductive resistances so as to keep either amperes or watts constant and to get the influence of the power factor on regulation.

Take a certain load, say 25% overload, entirely non-inductive, and gradually decrease it at the same time introducing more and more of an inductive load, say a choke coil in parallel with the load rheostat. Regulate the load so as to keep *total amperes constant,* and observe the variation of the secondary voltage as the power factor decreases. The same test can be repeated for say 100% load, and 75% load, etc.

Now take again a certain non-inductive load and gradually add to it some inductive load keeping *total watts constant.* Observe the regulation under these conditions. In this case it may be better to begin with the lowest power factor available (largest current) as otherwise the ammeter and wattmeter may be easily overloaded and damaged. Several curves can be taken for various values of watts.

Plot in your report the following curves:

(1) For non-inductive load plot secondary volts, secondary watts and primary amperes to secondary amperes as abscissae. As the voltage drop is very small plot it on the same curve sheet in per cent taking a larger scale for ordinates. This set of curves will give the voltage regulation of the transformer at non-inductive loads, and also will show that the currents are nearly as the inverse ratio of the voltages.

(2) Plot to power factor as abscissae, secondary amperes (constant), secondary voltage, voltage drop in per cent, secondary watts and primary amperes (nearly constant).

(3) Plot to power factor as abscissae curves similar to (2) for the runs where secondary watts were kept constant.

A comparison between all the above curves will give a clear picture of the regulation of the transformer under various conditions of the load.

Students working with the 2200 v. transformer must remember that *it is dangerous* to come in contact with the high-pressure side of it; great care should be exercised in regard to touching any switches, wire or instruments connected to the high-tension side. Rubber matting is put on the floor for protection, so as to insulate the students from the ground, and the students should not touch either the walls, the pipes or any objects that might be connected to the ground. In addition, rubber gloves are provided for the student who reads the high-tension instruments, so that he could not touch them by mistake. *Directions of the instructor should be followed exactly* and no changes attempted before consulting him.

An electrical engineer must inevitably handle high-tension currents in his practical work, and it seems, therefore, natural that he should have some experience with it before leaving college; he should know, however, that a mistake or negligence may prove fatal and should act accordingly.

2. Efficiency from losses.

The losses in a transformer consist of I^2R losses in both windings and iron loss, also commonly called *core loss* (hysteresis and eddy currents). Copper loss depends on the load exclusively and can be easily calculated for any load, if the ohmic resistances of both windings are known. Iron loss is practically independent of the load, because it depends only on the magnetic flux; the impressed voltage being constant, the flux is also nearly constant (neglecting the primary drop). Therefore the iron loss can be determined at no load and assumed to be the same at all loads. Ohmic resistances are measured by the ordinary direct-current method; core loss is measured by wattmeter method. It is not necessary to measure it from the high-tension side; 110 volts applied on the low tension side produce the same flux and give the same core loss as 2200 applied on the high-tension side. In performing this measurement be sure to disconnect the high-tension side from the power supply, otherwise you are liable to make a short circuit.

As an illustration, suppose that it is required to determine the efficiency of a 2200-110 v. 5 K. W. transformer at ¾ load. Let the

resistance of the windings be 10.7 ohm and 0.026 ohm respectively; let the iron loss as determined by wattmeter method be equal to 96 watts. At three-quarter load the output of the transformer is 3.75 K. W., or 34.2 amp. at 110 v. The primary current is 20 times less or 1.71 amp., so that we have

Primary copper loss	$1.71^2 \times 10.7$	= 31.2 watts.
Secondary " "	$34.2^2 \times 0.026$	= 30.4 "
Iron loss		= 96 "
Total losses at ¾ load		157.6 "

$$\text{Efficiency} = \frac{3750}{3750 + 157.6} = \text{about } 96\%.$$

In this way an efficiency curve can be plotted from no load up to say 50% overload.

3. Temperature Run.

When but one transformer is available for test, and the transformer is not too large, the run is usually conducted by actually loading it on resistances. The transformer is connected as in actual operation (Fig. 1), thermometers inserted into the windings, core, oil, and the transformer left under full load for 10 hours or until the temperature in all its parts has reacher the maximum limit. Temperatures of various parts plotted as abscissae gives the so-called *heating curve* of the transformer.

We have in the laboratory two identical transformers, so that instead of loading the transformers on resistances it is possible to run the test more economically by using the above mentioned "pumping back" method. The connections are shown in Fig. 2.

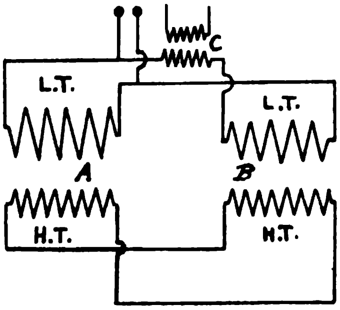

Fig. 2.

A and B are the two transformers under test; their low-tension windings are connected in parallel to the power supply, and the high tension windings are connected *in opposition to* each other. As the transformers are identical, no current flows through their secondaries and but a small magnetizing current flows through the low-tension windings. At the same time full iron loss takes place in the cores of the transformers, they being subjected to the full rated voltage. If now a full load current could be made to circulate in the windings, the transformers would be under the same conditions as regards heating as under actual full load. As we are concerned with I^2R loss only, it is not necessary that the current should be an alternating current of the same frequency; it can be a current of any frequency or even a direct current. If no suitable alternating current is available, both the high and the low tension circuits can be opened at some place and sources of direct current introduced sufficient to produce the desired currents in the windings.

A more convenient expedient is to open but one of the circuits, say the primary, and to introduce there a comparatively low source of alternating current of the same or of any frequency. This auxiliary source is shown in figure in the form of a transformer *C*. By regulating the voltage of this source a full-load current can be produced in the primaries of the transformers under test, and this current will induce a full-load current in the secondaries which thus do not need to be opened at all. This is very convenient since the secondaries are wound for a comparatively high voltage.

In this test the transformers are under actual load conditions in regard to losses and heating; at the same time the energy supplied from outside is merely sufficient to cover the losses. For instance, with two 1000 K. W. transformers having at full load an efficiency of about 98%, the total expenditure of power with the above test would be but 40 K. W.

In performing the temperature run according to Fig. 2, it must be borne in mind that the secondary is subjected to a high voltage the instant a low voltage is applied to the primary. *Therefore the students must be very careful not to put on any voltage whatever, until explicitly told to do so by the instructor, and should not touch any windings while the transformer is under test.*

During the run, the temperatures of both windings, of the core, the insulating oil and the case must be measured by thermometers every few minutes, in order to be able to plot the curves of temperature rise.

In addition, the temperature rise of the windings must be measured by the increase of resistance method at the beginning, at the end of the run, and at least once during the test. This is necessary because the thermometers show the temperature of the external part of the insulation only, while the temperature inside of the coil may be appreciably higher. The resistance is measured by the ordinary ammeter and voltmeter method, using direct current, 2½° C. rise in temperature corresponds to each 1% increase in resistance. In measuring the resistance during the test the readings must be made as rapidly as possible in order to prevent the transformer from getting cooled off. The best scheme is to have a double-throw switch arranged so that the transformer can instantly be switched over from alternating current to direct current and back. Be sure that the voltmeter leads are taken off while the current is put on or off, because a high induced e. m. f. during the variable state of the D. C. current may burn out the voltmeter.

Commercial transformers usually attain their final temperature after 10 hours run or thereabouts; therefore it is out of the question to attain this final state in the laboratory. The following method will make it possible *to predict* the final temperature and also to approximately figure out the maximum load which the transformer under test can carry continually. Theory and experiment show that heating curves of transformers have an aspect shown in Fig. 3; the equation of such curves is

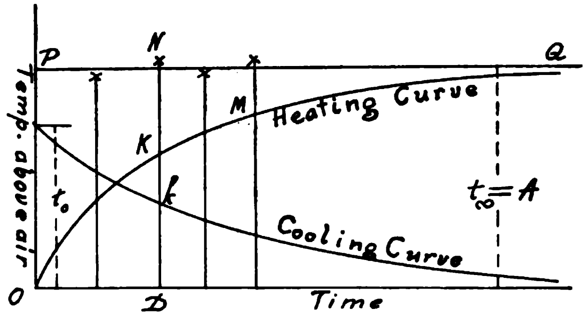

Fig. 8.

$$T = A\left(1 - e^{-Bx}\right) \text{............} (1) \quad \textit{(See Appendix.)}$$

where T is temperature, x time, and e the basis of Neperian logarithms; A and B are constants characterizing the given transformer and the

amount of energy converted into heat.(*) When $x = \infty$, $t_\infty = A$, so that A is the final temperature of the transformer. Having determined from the experiment a part of the curve, the coefficients A and B can be calculated and the rest of the curve constructed, or at least the final temperature $A = t_\infty$ calculated. As the above equation can be solved for B only by trials, which is a tedious process, it is advisable to determine B from another curve, the so-called "cooling curve" (Fig. 3). This is a curve which gives the temperature of the transformer when it is left to itself to be cooled off, the power being shut off. Theory shows that the equation of the cooling curve is

$$t = t_0 \cdot e^{-Bx}, \text{..........} (2)$$

where t_0 is the initial temperature when the transformer is hot. From this curve B can easily be calculated and then A determined from the heating curve.

The calculations can be arranged so that the inconvenient expression e^{-Bx} is entirely eliminated. This is done by substituting the value of this expression from the equation of the cooling curve into that of the heating curve; we find

$$T = A \left(1 - \frac{t}{t_0} \right) \text{..........} (3)$$

Suppose (Fig. 3) that OM is the part of the heating curve that was taken experimentally, and that it is desired to extend the curve beyond M and also to determine the ultimate temperature A. The cooling curve is supposed to be given throughout all its range; at any rate if a sufficiently long part of it has been determined experimentally it can be easily *extrapolated* by being plotted to a logarithmic scale, which converts it into a straight line.

Take a certain point K for which both $T = DK$ and $t = Dk$ are known, and substituting these values into the equation (3), determine $A = DN$. Do this for a sufficient number of points on the part OM of the heating curve, so as to be able to draw the line PQ with a sufficient accuracy. The ordinates of PQ represent the ultimate temperature to be expected under the given load conditions. To find points on the heat-

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*** In this and the following formulas the word "temperature" is used in the sense "temperature rise above that of the surrounding air."**

ing curve beyond M the same equation (3) can be used; the coefficient A is now known and T can be calculated for any value of t.

As the time of a laboratory period is not sufficient for attaining the final temperature of the transformers the students will have to use the above method of extrapolating the heating curve. It may occur that the load selected for the test was too high for the transformer, in other words the calculation may show that the ultimate temperature A is beyond that which the insulation of the transformer can safely stand. If this is the case the students will be expected to find out how many hours the transformer can stand this load until the highest allowable temperature is reached. Also what is the maximum load which the transformer can carry indefinitely, in other words what is the true rating of the transformer.

Suppose, for instance, that by this method the final temperature of the transformer was calculated to be 70° C. above the surrounding air. This is more than the safe limit, 50° C., which is allowed for ordinary transformers. Now the rating of the transformer for continuous load can be figured out as follows: Suppose that the iron loss during the test was 550 watts and copper loss 850 watts. Then we can say that a total loss of 1400 watts causes a rise of temperature of 70°; the loss that corresponds to a temperature rise of 50° is therefore equal to $1400 \times \frac{50}{70} = 1000$ watts, which allows $1000 - 550 = 450$ watts for copper loss. Thus the current during the test was $\sqrt{\frac{850}{450}} = 1.37$ times higher than should be allowed for continuous operation.

It may even occur that the transformers were run at such a high voltage that the temperature limit is exceeded with iron loss alone, at no load. This will show that the transformers were designed for a lower voltage or a higher frequency; for the iron loss depends on the flux, and the flux decreases directly with the voltage and inversely with the frequency.

Begin the experiment by taking a core loss curve for as wide a range of voltages as possible. Then arrange the scheme of connections as shown in Fig. 2 and provide necessary thermometers and a double-throw switch by means of which one of the transformers can be quickly and conveniently connected to either A. C. supply for the temperature run, or to a D. C. supply for measuring the resistances of the windings.

Measure the cold resistances and then begin the temperature run proper, continuing it for about two hours. Measure the temperatures say every 5 minutes, and from time to time measure the resistances as a check on temperature rise. The cooling curve of the transformer will be given to the students by the instructor, since it would take too long to observe it.

For the report plot the core loss curve to volts as abscissae; plot the cooling and the heating curves, calculate the ultimate temperature rise of the transformer, and find the maximum load which the transformer can carry indefinitely with a temperature rise of 50° C.

APPENDIX.

The above given expressions (1) and (2) for heating and cooling curves are based on the assumption that heat exchange between a warm body and the surrounding air is proportional to the excess of temperature of this body above that of the air. This assumption is confirmed by experience at least within the limits of temperatures at which electrical machinery is operating.

Let the excess of temperature of a cooling body over that of the air be t degrees Centigrade, and let K be the number of watts radiated in one second when the difference in temperature between the body and the surrounding air is 1°C. Then the number of watts radiated during an infinitesimally small element of time dx, is

$$Kt.dx.$$

On the other hand, if C is the number of watts necessary to communicate to the body in order to raise its temperature by 1°C, and the temperature of the body decreased by dt during the time dx, it lost Cdt watts, radiated through its surface; thus we have

$$Kt.dx + C.dt = O.$$

The integral of this equation is

$$\frac{K}{C} x = log \frac{t_o}{t} ,$$

where t_0 is the initial difference of temperature when $x = O$. Denoting $K \div C$ by B, and eliminating the logarithms we get the above given equation (2) of the cooling curve:

$$t = t_o . e^{-- Bx}$$

In deducing the equation of the heating curve we assume that W watts are continually communicated to the body from an external source and are converted into heat. In the specific case under consideration W represents the iron and the copper losses in the transformer. The body loses by radiation as before $Kt.dx$ watts and its increase in temperature dt is due to the difference $Wdx—Kt.dx$, or

$$W.dx - Kt.dx = C.dt.$$

This differential equation being integrated gives the above cited expression (1) for the heating curve.

These formulas have a practical meaning only if the temperatures of different parts within the transformer are fairly uniform, which is the case in a rationally designed transformer. Otherwise the temperature T in the heating curve has no definite meaning; T for some parts of the apparatus may be far beyond the safe limit, though the average T may be not excessive.

ASSEMBLING SWITCHBOARDS.

The switchboard is an essential part of every electric plant; its object being to group together at some convenient and accessible place the necessary devices for controlling and distributing the current to the various circuits, for measuring the power received or delivered, and for supporting safety devices which protect the machines and the lines.

The purpose of the laboratory exercise is to familiarize the students with the general disposition of apparatus on standard D. C. and A. C. switchboards; and also with the types and the functions of the principal switchboard devices and their electrical connections.

The generator switchboards represent the most important and in some respects the most interesting type, since they embody a larger variety of auxiliary apparatus than any other type. For this reason this type of switchboard is selected for the exercise. After having understood

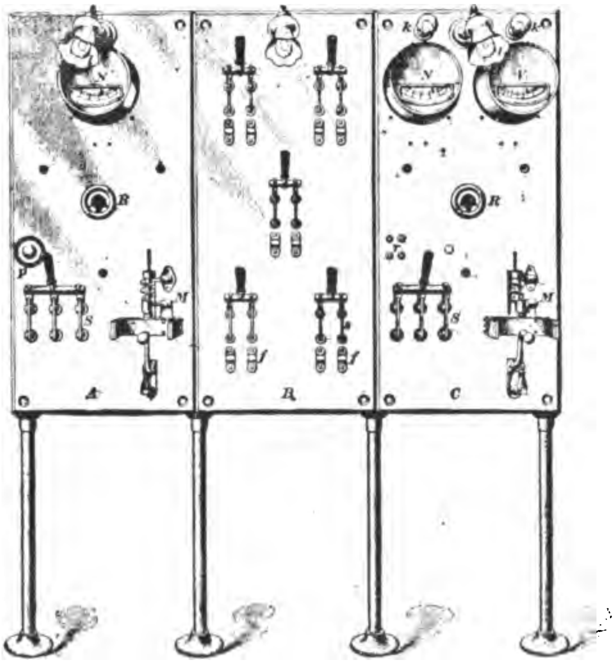

Fig. 1.

their construction and operation the students will have no difficulty in understanding the connections and the operation of the switchboards that are used for other purposes, as for instance those for controlling rotary convertors, synchronous and induction motors, arc lamps, etc.

In order to simplify the treatment direct current switchboards and alternating current switchboards are considered separately.

1. Direct-Current Switchboards.

A typical direct-current switchboard such as used in small isolated plants is shown in Fig. 1; Fig. 2 gives the corresponding scheme of connections. This switchboard is built for two compound-wound generators and five feeders. The two outside panels *A* and *C* are for the generators, the middle one *B* is for the feeders.

Both machines and all the feeders are connected to two external bus bars *xx* and *yy* (Fig. 2); the third bar *zz* is an equalizer between the series winding of the two machines and is used with compound-wound generators only. For a detailed explanation of the function of this equalizing bar see the Note on Operating direct-current generators in

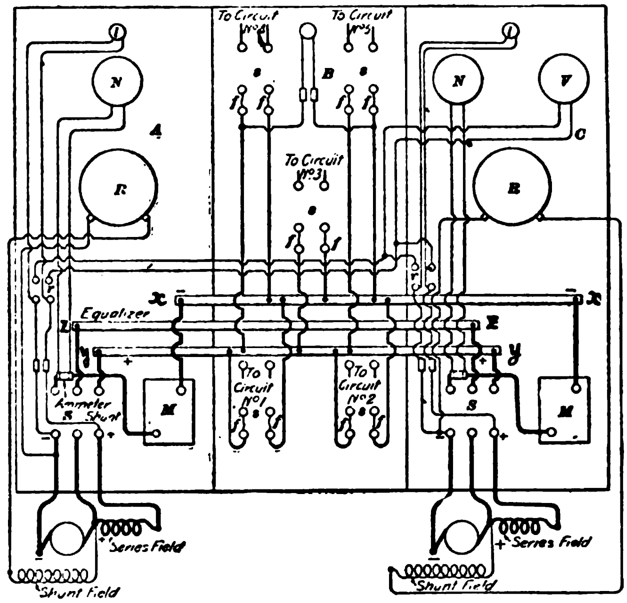

Fig. 2.

parallel; here it is sufficient to state, that should the voltage of the armature terminals of one of the machines for some reason be lower than that at the other machine, a current will flow through the equalizing bus bar to the series field of the weaker machine, and help to build up its voltage.

SS are the main switches of the machines; *MM* overload circuit breakers which automatically open the circuit should any of the machines become dangerously overloaded. Ammeters *NN* have external shunts mounted near the main switches, so that only small leads need be taken to the instruments themselves. Only one voltmeter *V* is used on the switchboard; it can be connected to show the voltage of either machine by means of a removable plug, which can be put into the receptacle, *r*, of either machine.

The lamps, *ll*, are connected so that they light up as soon as the machine is excited, though the main switch may be still open; in this way they act as pilot lamps in addition to illuminating the dials of the instruments. The lamps, *kk* (Fig. 1) are for detecting grounds on the line; one is connected between the + bus bar and the ground, the other between the — bus bar and the ground. Lamps of a sufficiently high voltage are selected for this purpose, so that when there is no ground on the line they burn dull red; the presence of the ground is indicated by one lamp burning brighter than the other. *RR* are the field rheostats of the generators; they are mounted on the back of the switchboard, only the operating handles projecting on the front.

The above scheme is somewhat simplified if the generators are shunt-wound: the equalizing bus bar is then omitted and the generator switches are double-pole instead of three-pole. However in large stations separate single pole switches are used with compound-wound generators, and the equalizing connection is made directly by a cable between the machines without bringing it to the switchboard. The reason for this is explained in the above referred to note on parallel running of direct-current generators.

A complication of the above scheme arises when a storage battery is provided in parallel with the generators. The purpose of the battery is to take up the fluctuations of the load; to act as a temporary relay in case one of the machines is disabled, and also, sometimes, to take up the entire load of the station during the hours of light load. The exact scheme of connections in this case depends on the character of the

work which the battery is called on to perform, on the method of charging the battery, and also whether or not the battery remains connected to the line while being charged.

The simplest way to charge a storage battery is to raise the voltage of one of the generators so as to get the necessary pressure for charging; while this is done the generator must of course be disconnected from the lighting circuit. Another method is to connect the two halves of the battery in parallel and to put some regulating resistance in series with it so as to keep the proper value of the charging current. With this scheme, the generator can simultaneously charge the battery and send the current into the line. With large batteries, a loss of power in the rheostat is an objection to this method.

A better way of charging the battery is by means of a booster (Fig. 3). A booster is an auxiliary generator, *B*, separately excited and connected into the battery circuit so as to be in series with the main generator *G*. The booster is driven by a separate motor, *M*, usually direct-connected to it. By properly exciting the booster, the voltage at the terminals of the storage battery is raised sufficiently to charge the battery. When the battery is discharging into the line, the switch, *F*, is thrown down, so that the booster circuit is open. The arrangement *dec* is called the "end-cell switch"; by means of it more or less cells are connected into the circuit, so as to maintain the proper voltage during the discharge. This is necessary because the voltage of the battery is higher at the beginning of the discharge and then gradually drops as the discharge goes on.

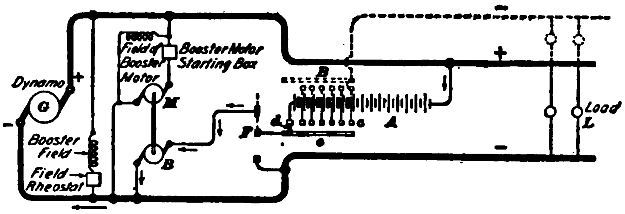

Fig. 8.

Another end-cell switch is shown in the sketch by dotted lines; it can be used for another group of lamps in case the drop of voltage is considerable in the main line, and there is, near the battery, a small group of lamps to which the drop is comparatively small.

The arrangement of the booster and the battery shown in Fig. 3 is the simplest possible, and though there are many better and more complicated schemes for connecting boosters and batteries, an understanding of the above scheme is sufficient for this exercise. Boosters are also used in railway power houses and substations with or without storage batteries for compensating the drop in long feeders; this is shown schematically in Fig. 4. *A* is the main generator or a rotary convertor, *B* is a booster usually driven by a direct-connected electric motor; *ab* and *cd* are the station-bus bars. Two feeders, *e* and *f*, are shown, one feeding the adjacent part, *C*, of the trolley line at the generator voltage, the other one connected to a more removed section, *D*, of the line and feeding it through the booster.

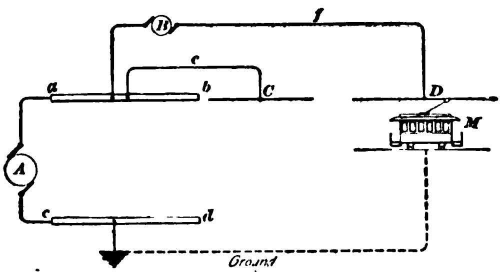

Fig. 4.

Another complication of the scheme Fig. 3 arises when the power is to be supplied to a three-wire line (Figs. 5 and 6). The three-wire system is used on large lighting circuits to save the expense in line copper; it is also used on motor circuits for running the motors over a wider range of speed than is possible with the ordinary two-wire system. There are different methods for dividing the generator voltage; Fig. 5 shows the use of a storage battery, and Fig. 6 illustrates the application of a "balancer set," consisting of two identical machines connected across the line. The middle wire of the system is connected at *n*, where the

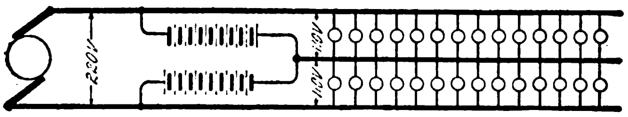

Fig. 5.

two machines of the balancer set are connected; the two machines being identical, the total voltage is evenly divided by two at this point. The figure illustrates the case of an unbalanced load; machine *a* working as a generator, *a'* as a motor. 12 lamps are burning between + and O, and 6 lamps between O and —, giving a load of 6 amperes and 3 amperes respectively. The main generator, *A*, supplies 4½ amps., the machine, *a*, supplies the remaining 1½ amps. 3 amps return to the main generator directly through the lamps, and 1½ amps through the machine, *a*, driving it as a motor and supplying the necessary power for generating 1½ amps. in the machine *a*. In reality the distribution of the current is somewhat different because of the losses in the balancer set, but the general idea is the same.

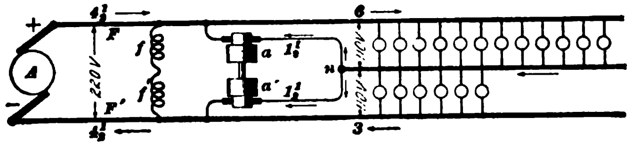

Fig. 6.

In case a battery, a booster, a balancer set, etc., are used in the station an additional panel on the switchboard becomes necessary for mounting the necessary switches, instruments and rheostats. With a clear understanding of the action of the above auxiliaries, the students will have no difficulty in making schemes of connections to suit the given requirements.

The students will be given in the laboratory a switchboard frame and a supply of switches, bus bars, wire, ammeters, voltmeters, rheostats, lightning arresters, etc. The work consists in designing a scheme of connections, similar to that shown in Fig. 2, possibly with the addition of a panel for a storage battery, a booster, a motor-generator set, etc., as indicated by the instructor, and then in actually assembling the necessary apparatus on the switchboard.

In doing this work particular attention should be paid to placing all the devices systematically and so that they occupy a minimum space. All similar devices should be placed if possible in one horizontal row, for instance the measuring instruments must occupy such a height as

to be conveniently read by the switchboard attendant; the circuit breakers must be placed in the top row, so as not to hit the attendant when opening the circuit. The rheostat handles should be placed so that the attendant could operate them, at the same time watching the instruments; the switches are placed where the space is available, usually in the lower row. The integrating wattmeters are read but once a week or so, and can, therefore, be mounted at any place, even on the wall outside the switchboard, if no other space is available.

All the wiring must be placed on the rear of the switchboard; the work must be done neatly, be all visible and securely fastened in the right position. No slanted wires are allowed as a rule;. the wires must run either horizontal or vertical with a sharp bent.

Having finished the work check your work by operating the switchboard in the way it would be operated in practice, when

(a) starting the plant,
(b) changing from one machine to another, or adding a new machine,
(c) shutting down a machine or the whole plant,
(d) in case of an emergency of any kind.

During the laboratory period the students will be given the exact size and voltage of the plant, for which they are assembling the switchboard. Of course in the laboratory, for practice in assembling, any switches and instruments available can be used, but in the report the sizes of the auxiliaries must be calculated as follows:

(a) switches: Suppose for instance that the size of your plant is 500kw and the pressure 250v. If there are two machines, each machine must have a capacity of 250kw, and at 250v. delivered at full load 1000 amp. This is the maximum current which the main switches will have to carry continuously. Of course some margin should be allowed for possible short overloads, say 50%, but the exact percentage of this allowance entirely depends on the character of the plant and the duty for which it is intended. It seems that the above figure 50% fairly well represents the average conditions. Thus the switches must be of a 1000 amp. 250v. type, and capable of opening the circuit when carrying a load of 1500 amperes.

(b) The range of ***main ammeters*** is calculated in the same way as that of the switches.

(c) bus bars: a table will be found in Foster's Pocket Book, p. 587, giving the sizes for various current-carrying capacity.

(d) field rheostats: their range is usually given in ohms and in amperes carrying capacity with all rheostat "in," and "out." According to the size of the machines from 2 to 5% of the main current is consumed for field excitation; this gives the amperage of the rheostat. For instance, in the above example the maximum field current of each machine can be assumed to be about 35 amps. This means that the total resistance of the field winding when the rheostat is all "out," is 250 ÷ 35 = about 7 ohms. It is customary to give the field rheostat such a resistance that the field current could be reduced to ½ full value. Thus in our case the resistance of the field rheostat must be also about 7 ohms, and its current carrying parts must be dimensioned that it might stand continually and without excessive heating, 35 amps. and with the resistance all "out," and about 18 amps. with the resistance all "in" (this is what is called in practice "taper 2:1" rheostat).

(e) Overload circuit breakers or fuses. They should open the circuit when the current exceeds a certain percentage (say 50%) of the full rated capacity of a machine; their size is figured out in the same way as that of the switches and ammeters.

(f) Voltmeters. 110v. plants are usuallly supplied with 150v. scale instruments; 250v. plans with 300v. instruments, etc.; this gives in each case a sufficient margin should the voltage for some reason rise above normal.

(g) Integrating wattmeters. These are rated in volts and amperes; for instance in the above example a wattmeter must be used whose series windings can stand about 3000 amps. as a maximum on overloads (2000 amps. continual capacity), and the potential winding provided with a multiplier for 250v.

(h) Cables to generators are figured out from tables giving safe carrying capacity for various conductors.

(i) Battery and booster auxiliaries are figured out in a similar way either for the current which they have to carry, or for the voltage which is applied at their terminals.

Your report must comprise:

(1) A diagram of connections similar to that shown in Fig. 2. Do not copy this diagram; merely refer to it and give a diagram of additional parts not contained in this figure (for instance the battery and the

booster), or indicate if your scheme of connections was in a certain respect different from that shown in Fig. 2.

(2) The sizes of switchboard apparatus to be used with the particular size switchboard given you, as explained above.

(3) A short instruction for operating the switchboard when starting, shutting down the plant, changing from one machine to the other, and in case of an emergency.

NOTE Catalogues of leading manufacturers of switches, circuit breakers, measuring instruments and rheostats are placed for reference in the E. E. design room. After having figured out the sizes of the above auxiliaries the students should find in these catalogues the types of devices that come the nearest to their requirements and specify them in their report using the manufacturer's notation. This will give an opportunity for becoming acquainted with the commercial types of principal electrical devices and with the way in which they are usually selected and ordered from the manufacturers.

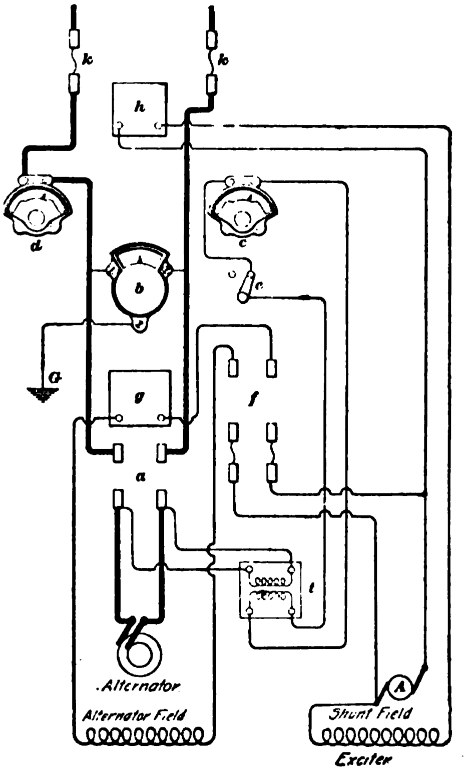

Fig. 7.

2. *Alternating-Current Switchboards.*

A simple diagram of connections such as are used in small isolated single-phase plants is shown in Fig. 7. The main circuit is indicated by heavy lines; *a* is the main switch, *d* an ammeter and *kk* fuses. Voltage is measured on voltmeter, *c*, which in this particular case is connected to the machine terminals through a small transformer, *t*. This is usually done on circuits above 1000 v., as otherwise the voltmeter multiplier becomes too expensive, and the instrument dangerous to handle. *A* is a shunt-wound exciter, a small direct-current machine which supplies current for energizing the field of the alternator. The exciting current passes from *A* through the switch *f* and regulating rheostat *g* into the alternator field. In addition to regulating the excitation of the alternator by *g*, a rheostat *h* is provided in the field of the exciter; this gives a finer and more economical regulation. A ground detector *b* is connected across the mains. The instrument is essentially an electrostatic voltmeter: the two line wires are connected to two stationary elements, the movable element is connected to the ground. When the insulation of the line is perfect, equal static charges are induced on both ends of the moving element; when one of the wires is grounded, the movable element is attractd more strongly to the side which is not grounded; this is shown by a pointer on the scale. The scale can be calibrated in ohms or in any arbitrary units. Instead of a ground detector, lamps can be used as explained above for direct-current switchboards.

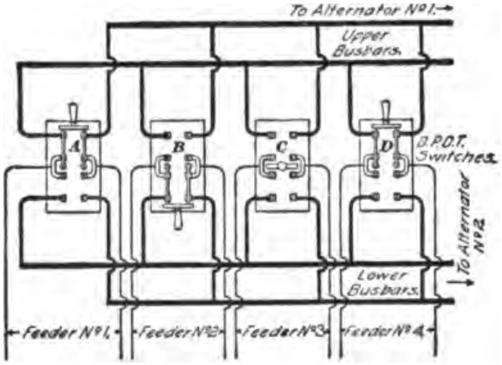

Fig. 8.

In most plants two or more generators are provided, partly as a relay and also to make it possible to run one small machine during the

hours of light load; more machines being added as the load increases. Several generators can be run on the same bus bars (See Note on alternators in parallel), but as this brings in some additional complications and as the machines do not always run satisfactorily in parallel, particularly if driven by gas engines, it is often preferred in small installations to run the machines separately, distributing the load between them as well as possible. Such an arrangement is shown in Fig. 8. One alternator is connected to the upper bus bars, the other to the lower ones. The out-going switches are connected to double-throw switches and can be supplied with current from either machine.

When two or more alternators are run in parallel on the same bus bars, connections are used as shown in Fig. 9, in application to two three-

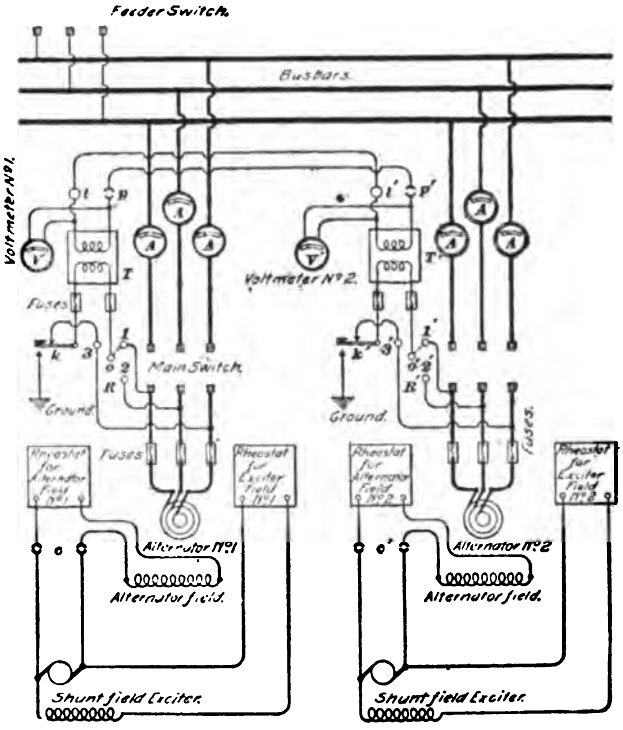

Fig. 9.

phase alternators. The general connections for each alternator are the same as in Fig. 1: the main circuit of each alternator contains fuses, a switch and ammeters; the exciter circuit is the same as in Fig. 1,

as is also the voltmeter circuit. The only addition is the line connecting the two voltmeters and used for synchronizing the alternators before throwing them in parallel; *l* and *l'* are synchronizing lamps and *p* and *p'*

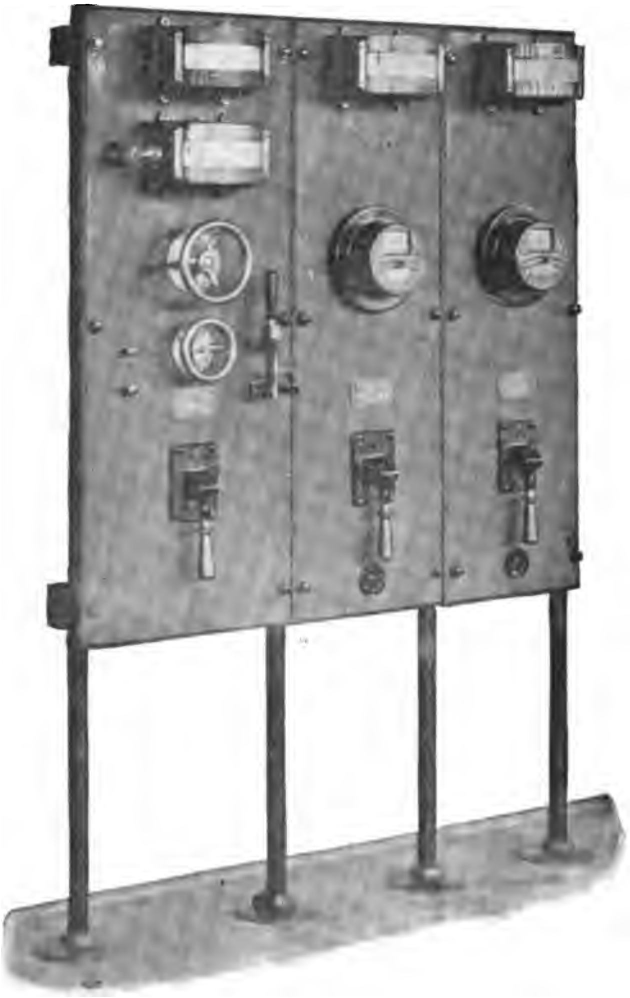

Fig. 10.

plugs which open the synchronizing connection. Voltmeters switches *R R'* are provided permitting the measurement of the voltage between the phases 1-3 and 2-3, and also to test all three phases for the grounds. Frequently but one voltmeter with a removable plug is used for a num-

ber of machines, as shown in Fig. 11. Figs. 10 and 11 represent two examples of small alternating current switchboards; the same apparatus is mounted as shown in Figs. 7 and 9. The left hand panel in Fig. 10 is the generator panel; the other two are feeder panels. On the generator panel an oil switch for opening the main circuit can be seen, two rheostat hand-wheels, a voltmeter and an ammeter; the switch beside the hand-wheels opens the field circuit. Each feeder panel has an ammeter, an integrating meter and an automatic oil switch (circuit breaker).

The switchboard in Fig. 11 is built for two three-phase alternators and one feeder panel. As the number of generators or feeders increases, additional panels are added to the left or to the right. Instead of oil switches, ordinary quick-break knife switches are used; the field circuit

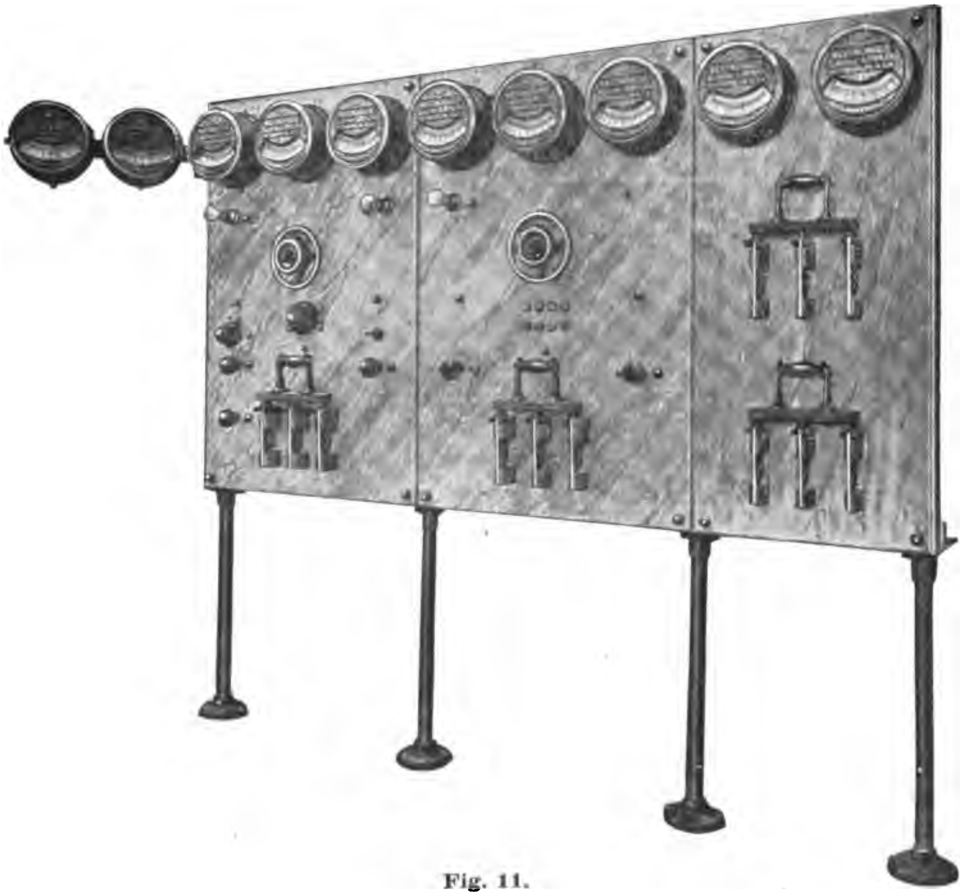

Fig. 11.

is opened by plug switches whose handles are seen on both sides of the main generator. Ammeters are inserted in all three phases of generator leads. Voltmeters are mounted on a swinging bracket in order to save space and also to make them visible from any desired position. One voltmeter is connected to the main bus bar, the other is used for synchronizing. The two rheostat handles are mounted concentrically one inside the other for economy in space.

However large the units are, the general scheme of connections remains the same, only additional instruments are sometimes put on the switchboard in order to enable the attendant to more closely follow the operation of the machines. As such special instruments, indicating wattmeters, power factor indicators and recording voltmeters are frequently used in large power houses; also sometimes synchroscopes, frequency meters, reverse-current relays, etc. All such instruments can be added to the fundamental scheme and without changing it in its principle.

Indicating wattmeters and power factor indicators have two windings: a series winding and a shunt or potential winding. The first is connected in series with the main circuit, if necessary through a suitable series transformer; the latter across the circuit, also is necessary through a voltage reducing transformer. Synchroscopes and frequency meters are connected in the same way as voltmeters, viz., across the bus bars. In some cases these instruments are connected to the same series and shunt transformers with the main ammeters and voltmeters; in most cases, sowever, they should be provided with their own transformers.

The exercise in assembling A. C. switchboards is performed in the laboratory in a similar way to that described above for direct-current switchboards, except that other instruments and different schemes of connections are used. In addition to the scheme shown in Fig. 9, the students may possibly be asked to connect into the circuit some additional devices, as for instance a power factor meter, a frequency indicator, a polyphase indicating wattmeter, etc., and possibly to wire up an additional panel for a rotary convertor, a synchronous or an induction motor, an arc light circuit, etc.

The report must comprise the same three points as mentioned above for direct-current switchboards.

ELECTRIC CONTROLLERS.

When an electric motor has to be started and stopped but a few times during the day, and is intended to run at a constant speed, the necessary auxiliary apparatus consists merely of a switch, a pair of fuses and a starting rheostat. When, however the motor has to be started and stopped several hundred and even thousands of times a day, as is the case in railway, elevator, crane service, etc., and when in addition, the operator has at the same time to watch other things besides the motor, the problem is entirely different. The controlling apparatus must in this case be amply strong so as to stand rough usage, having in mind the hard service of a motorman or an elevator boy. However intricate its inner connections may be, it must possess an ideal simplicity of

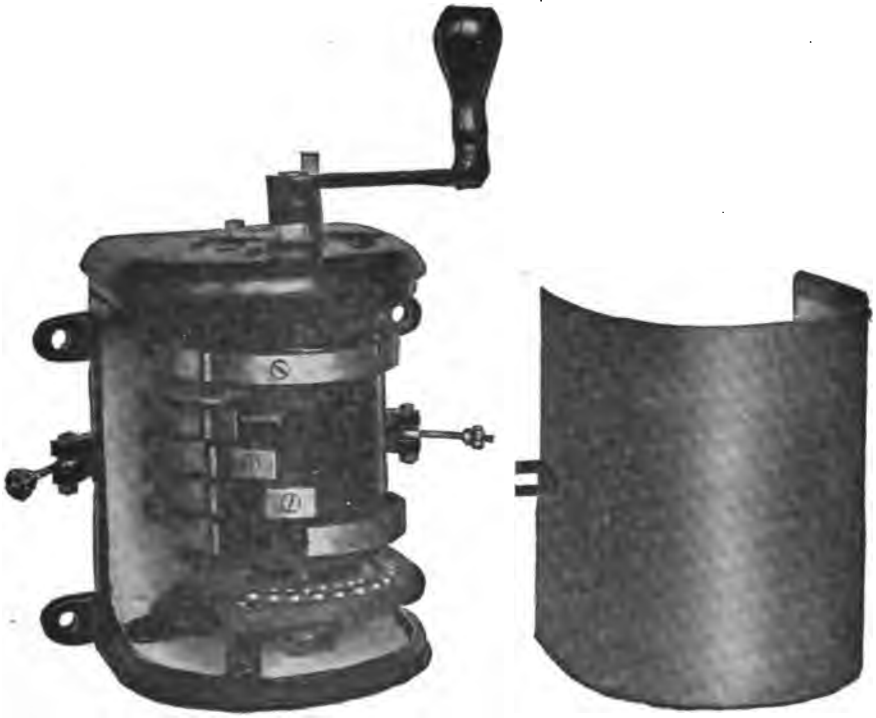

Fig. 1.

operation. One handle for all operations is the goal of the designer of such motor controlling devices, because if there is more than one handle there is always a chance for the operator to make a wrong and possibly disastrous move.

Devices used for starting, stopping, regulating the speed, and reversing electric motors are generally called *controllers*. There are three principal forms of controllers in practical use: drum type controller (Fig. 1), face-plate controller (Fig 2) and switch type controller consisting of several individual switches such as shown in Figs 3*a* and 3*b*.

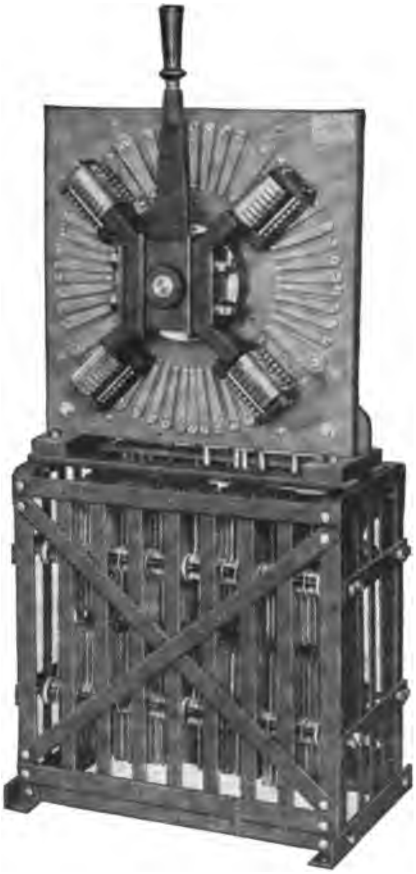

Fig. 2.

The difference between these types is purely in the mechanical con-

struction; from an electrical point of view the same operations can be performed by a controller of either type. This is best illustrated by some

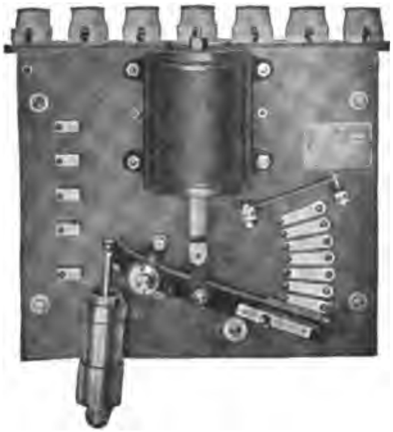

Fig. 3a.

examples from railway practice. The earliest street-car controllers were of a face-plate type; modern city car controllers are of the drum type, while large interurban and rapid transit cars are mostly equipped with individual-switch type controllers.

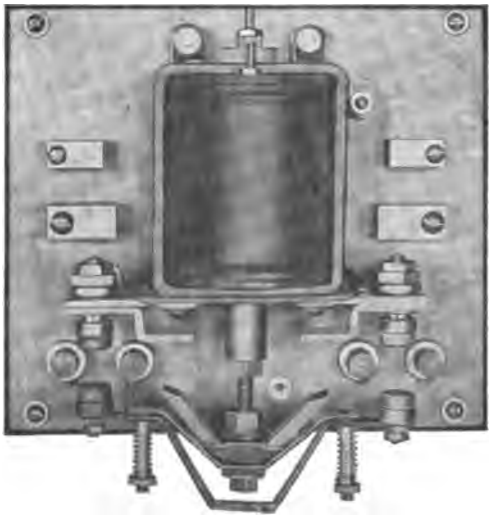

Fig. 3b.

In face-plate controllers (Fig. 2) wires from the motor, from the rheostat and from the line, are all connected to suitable pieces on a slate plate; these contact pieces are then combined into suitable combinations by copper or carbon brushes mounted on a lever which can sweep over these contact pieces. In the drum-type controller (Fig. 1) the various parts of the circuit are connected to the stationary controller "fingers" and these are brought into the necessary combinations by the connecting copper pieces mounted on the revolving drum. The drum is operated by a handle, and in each position of the handle different fingers are connected in a different way, so as to vary the speed of the motor, the direction of rotation, etc, Individual switch controllers are used for large currents, or where a control from a distance is desired. The individual switches are operated either electrically by means of solenoids (Figs. 3*a* and *b*), or mechanically by compressed air. In either case the operator merely closes an auxiliary circuit, which either operates the solenoids or opens the valve of an air cylinder.

Controllers are chiefly used on electric cars, for crane and elevator service, and in connection with electrically operated machine tools, especially those individually driven by electric motors and requiring speed regulation.

The purpose of the laboratory exercise with controllers is to familiarize the students with the various types of electric controllers, their connections, mechanical features and safety devices. The railway controller being more important and more complicated than the others is described separately; the rest are comprised under the heading "Machine-Tool Controllers" though in reality the description also includes some features of crane and elevator controllers.

1. Electric Car Controller.

The laboratory equipment for this exercise consists of a street-car truck with two motors mounted on it and a regular series-parallel controller such as we see on street-car platforms. The students are expected to connect up the motors to the controller and to the power supply and to operate the truck as if it were an actual car. The truck is blocked up and the wheels are free to rotate in the air.

Motors used for railway work are series wound, and in starting the car, the armatures of the motors, their fields and some additional resistance are all connected in series in order to limit the rush of current.

As the car acquires speed, the starting resistance may be gradually cut off, because the counter-electromotive force of the motors prevents an excessive rush of the current from the line. When all of the resistance is cut off the two motors run in series *at half speed,* because if the line voltage is, for instance, 500 v., each motor has only 250 v. at its terminals. To increase the speed, the motors are now connected in parallel, so that each has 500 v. pressure. Before this is done, some starting resistance is again inserted into the circuit, to avoid a sudden jerk and rush of current in changing from half speed to full speed. Then as the car goes faster, this resistance is again gradually cut out until the two motors are connected directly across the 500 v. in parallel and the car runs *at full speed.*

The speed can be further increased by weakening the field of the motors; this is done by shunting the fields by special resistances; this shunting of fields is not much used at present, but may be useful in some special classes of service.

In stopping the car, the motorman first shuts off the power and then applies the brakes. Three kinds of brakes are in use at present: hand brakes, air brakes and electric brakes. Each car is necessarily provided with a hand brake, either for regular or for emergency service; cars in large cities, high-speed suburban and inter-urban cars, cars running on roads with long and steep grades, etc., are usually provided with power brakes (air operated or electric). It would be out of place here to go into a discussion of relative advantages of these two kinds of power brakes; both are in successful operation on many different roads both in this country and abroad. Air brakes are operated independently of the electric equipment, while with the electric (or as they are now called magnetic) brakes the same motors are used for braking as for driving the car.

The principle of magnetic braking is substantially as follows: the motors are disconnected from the trolley line supply and their fields and armatures are connected in such a way that they act *as generators,* utilizing the acquired momentum of the car for producing current; the car is provided with brake shoes made in the form of electromagnets, which are placed either near the rails or near special iron discs on the axles. The current generated by the motors is sent through these electro-magnets; they become energized and press themselves against the rails or the discs on the axles, thus producing friction which tends to stop the car; the in-

tensity of braking is regulated by the amount of resistance in the circuit.

Formerly a method of electric braking has been used, which simply consisted in closing the motors, acting as generators, on resistances in which the stored energy was dissipated in the form of heat. This method of braking has been abandoned, because it is liable to overload the motors; they have no chance to get cooled off while the car is coasting, say, down a long grade.

The controller which we have in the laboratory is adapted to be used with a magnetic brake, and allows of the following three principal combinations of motors:

(1) Motors in series,—half speed (Fig. 4);

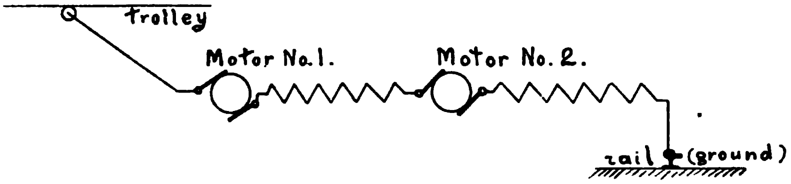

Fig. 4.

(2) Motors in parallel,—full speed (Fig. 5);

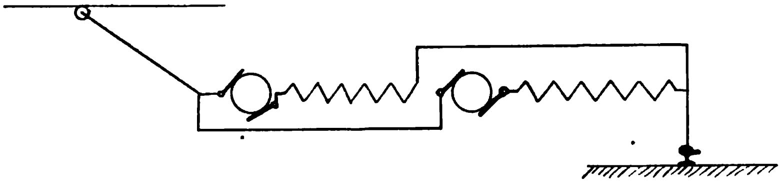

Fig. 5.

(3) Motors acting as generators for braking (Fig. 6).

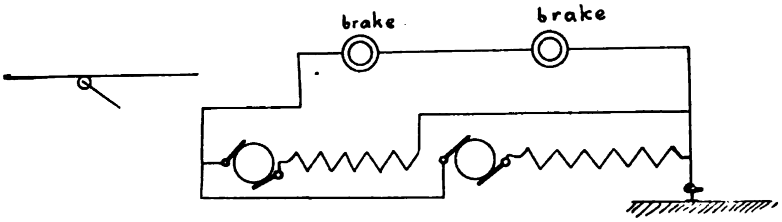

Fig. 6.

For each of these principal combinations there are, on the controller.

several intermediate positions on which the resistance is gradually cut out. The controller in our laboratory has 5 operating points with motors in series, 4 points with motors in parallel and 6 brake points.

Different combinations are obtained by means of a revolving drum and contact fingers. The drum has copper strips properly interconnected; contact fingers are stationary and connected to the motors, resistances, brakes, trolley, ground (truck), etc. In different positions of the drum, operated by the motorman, various fingers are differently connected by the strips on the drum, so as to give suitable combinations of motors, resistances, etc.

In speaking about controller connections it is customary to develop the drum and to indicate different positions of the motorman's handle by vertical dotted lines, as shown in Figs. 7, 8 and 9 on the large scheme of controller connections attached to this note. In this way all the combinations can be easily followed out on the paper.

Before attempting to follow in detail this complete scheme it is advisable to first clearly understand the three simple diagrams shown in Figs. 7, 8 and 9. The complete diagram is a combination of these three schemes; so far as possible the same letters are used in the auxiliary schemes as in the complete diagram.

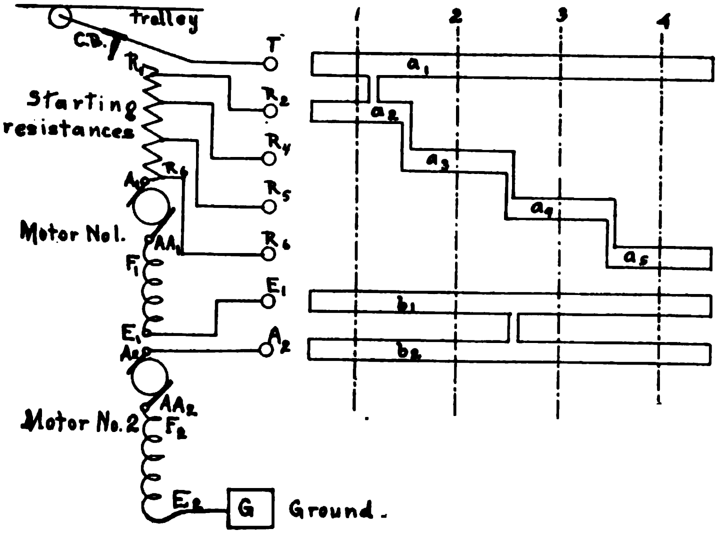

Fig. 7.

Starting the car with the motors in series (Fig. 7). On the first notch current from the trolley flows through the circuit breaker *CB* to the finger *T* and thence through the strips a_1 and a_2 to the finger R_2; now since the fingers R_4, R_5 and R_6 do not touch the corresponding strips a_3, a_4 and a_5, the current flows through the whole resistance R_2R_6, through the motor No. 1 to the finger E_1; thence through b_1 and b_2 to the motor No. 2 and finally to the ground *G*. (*)

On the second notch the current finds a shorter way from *T* through a_1, a_2 and a_3 to the contact finger R_4, so that part of the resistance between R_2 and R_4 is cut out; in other respects the current follows the same path as before. On the third notch contact R_5 becomes operative; finally on the fourth notch the current from *T* follows directly through a_1, a_2, a_3, a_4 and a_5 into the armature of the first motor, so that the whole resistance R_1R_6 is cut out of the circuit; this gives the *full series* (half speed) connection.

When you see on a controller scheme a diagonal chain of strips like a_2, a_3, a_4, a_5, it usually means a gradual cutting in or out of some resist-

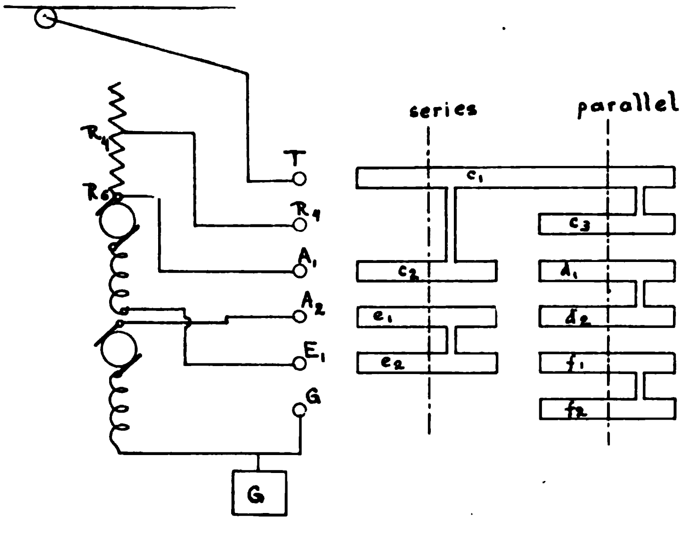

Fig. 8.

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* Only *one* wire (trolley wire) is used in electric railway circuits, the current returning to the dynamo through the rails; the ground on the car is obtained by connecting the wire *G* to the truck; the current flows through the truck axles and wheels to the rails; one of the bus bars in the station is also connected to the rails.

ance. The motorman is not allowed to ride for any length of time on these "resistance points", but only to use them for starting. The resistances that are put into cars are not large enough to be permanently connected into the circuit; they would get excessively hot and might burn out.

(2) *Change from series to parallel.* To change from half speed to full speed the connection will have to be changed from series to parallel, and some resistance again introduced into the circuit. The fingers and strips that are operative in this change are shown in Fig. 8. With motors in series the current from the trolley finger *T* through c_1 and c_2 flows into the first motor; then through e_1 and e_2 to the second motor and thence to the ground. On the first "parallel" notch the current from *T* through c_1 and c_2 flows to the resistance R_4 R_6 and then *is divided* into

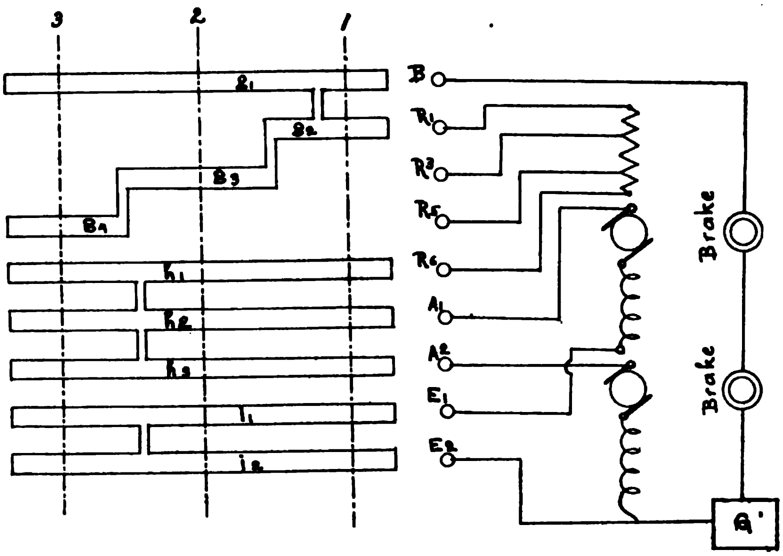
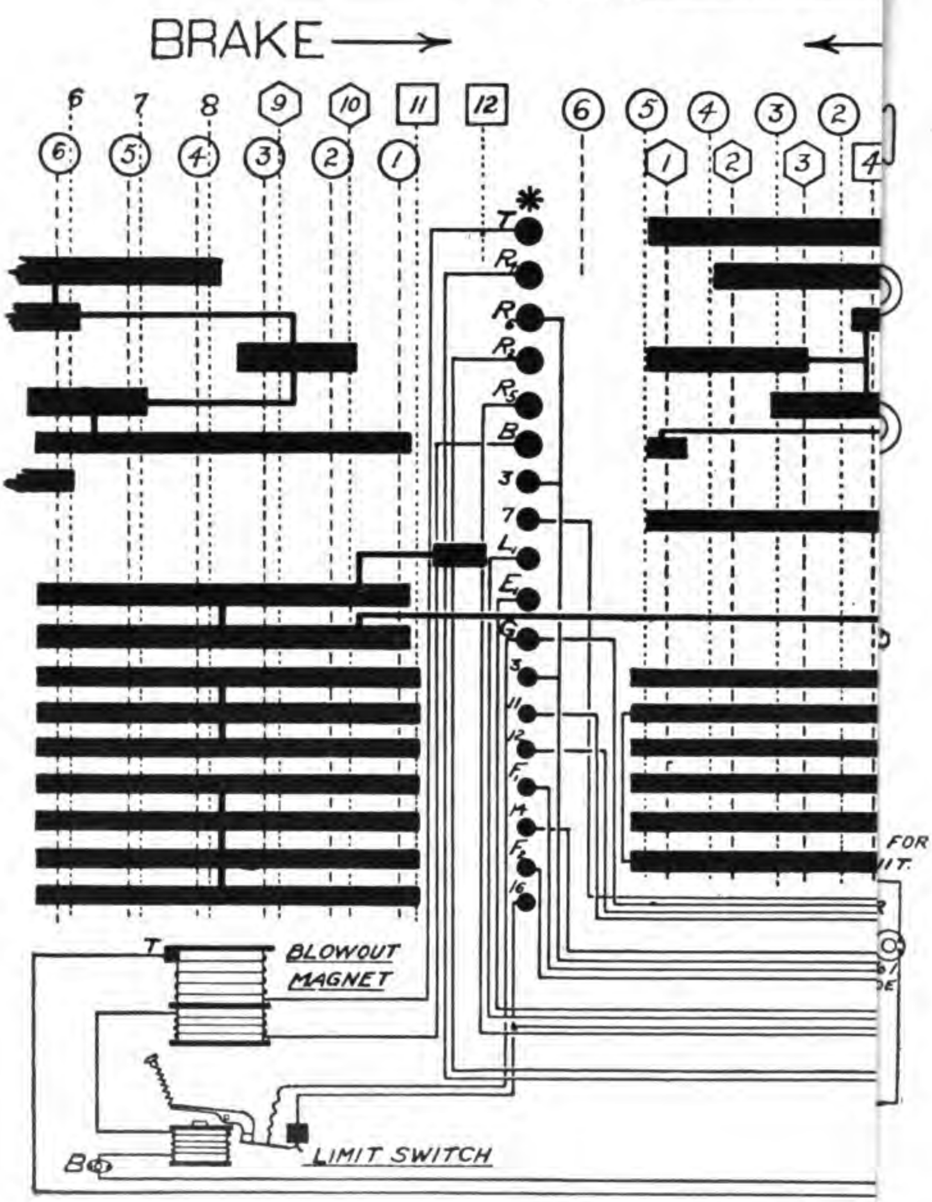


Fig. 9.

CONNECTIONS A



⬡ *INDICATES RESISTACE POINTS.* ○ *INDIC*

□ *INDICATES RUNNING POINTS.* *6,7,8 IN* two halves: one half follows the path—motor No. 1, E_1, f_1, f_2, G to the ground; the other half—finger A_1, d_1, d_2, A_2, motor No. 2 to the ground. On the next notches the resistance is gradually cut out until the motors are in "full parallel".

(3) *Braking.* As was explained before, the motors must supply current to the brake circuit acting as generators; the amount of braking is determined by the speed of the car and the value of the resistance in the circuit. Controller connections for braking are shown in Fig. 9. The two motors are connected in parallel by the strips i_1 and i_2 on one side and h_2 and h_3 on the other side; the current generated in both motors flows through h_1 and resistances R to the strip g_1 and thence through the contact finger B to the brakes; the circuit is completed through the ground G. The three positions shown in sketch differ only by the amount of the resistance R in the circuit.

Combining now the three above schemes in one we get the actual controller which connects the motors in series or parallel, regulates the resistance of the circuit, and makes the connections for braking.

A glance at the attached diagram of connections of an actual controller (see folded page) shows, however, that it is somewhat more complicated than a mere combination of the three above schemes. This additional complication arises from the following causes:

(1) The connections should be such as to make it possible to reverse the motors for running in either direction.

(2) Change from series to parallel must be made without breaking the circuit (to avoid sparking).

(3) Switches must be provided that enable the motorman to cut out one of the motors if it should become disabled and to complete the trip with the other motor.

(4) Contact points (high-speed points) should be provided for shunting the fields.

(5) A current-limiting device must be provided that would prevent the motorman from applying the brakes too suddenly.

(6) A scheme should be provided for quickly demagnetizing the brakes when the power is again applied.

In addition to these, the requirements of construction and insulation necessitate a somewhat different disposition of controller fingers and drum strips than that indicated above. However, keeping the above three fundamental schemes (Figs. 7, 8 and 9) in mind, the following up

of the actual connections will hardly offer serious difficulties. The six above mentioned additional requirements are taken care of by the following means:

(1) *Reversing motors.* Motors are reversed by interchanging the armature leads; a separate drum with a handle is provided in the controller for this purpose. In its principle it is an ordinary double-throw switch; the connections can be readily followed up in the general diagram.

(2) *Change from series to parallel without breaking the circuit* is effected as follows: (Fig 10)

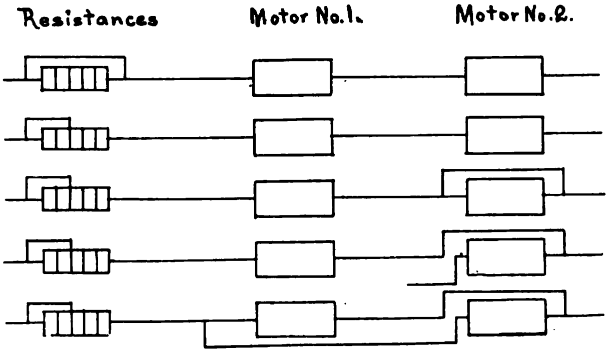


Fig. 10.

First some resistance is introduced, then Motor No. 2 is short-circuited (or, which amounts to the same, motor No. 1 is grounded around it); after this the circuit of the second motor is opened and the connection changed from series to parallel. These changes are made in the positions 6 to 8 of the controller handle (the so-called transition points), and the motorman should pass these points without stopping at them.

(3) *Switches for disconnecting a disabled motor* are placed under the reversing drum; it will be seen from the scheme of connections that if Motor No. 1 is disabled and the motorman opens the corresponding switch, a by-pass is offered to the current through the auxiliary contact marked "*8* and R_6", to motor No. 2, while the field, armature and shunt circuits of the disabled motor are opened. If motor No. 2 is disabled and its switch opened, a by-pass to the ground is offered by the auxiliary contact marked *G*, behind the switch, while the field and armature circuits of the disabled motor are opened.

(4) *Points with fields shunted* are: No. 5 for motors in series and No. 12 for motors in parallel; shunts around the fields of the motors are permanently connected to the fields on one side. On the above mentioned points, contact fingers L_1 and L_2 become operative and close the other side of the circuit, thus weakening the fields and increasing the speed of the motors. This is obtained, of course, at the expense of a considerably increased armature current. For this latter reason these points should not be used except on level or nearly level and straight portions of the road.

(5) *Current limiting device for brakes* consists of an electromagnet placed somewhere outside of the controller and connected into the brake circuit (this limit switch is shown in the left lower corner of the large diagram). When the braking current rises beyond a certain limit this electro-magnet closes a switch which short-circuits the fields of the motors; this decreases the main current and the electro-magnet again releases the switch. No circuit-breaker or fuse could be used for this purpose, because the device must be *self-restoring*. Make this clear to yourself.

(6) *Brakes must be demagnetized* before power is put on, on account of residual magnetism which keeps them attracted even after the current has been shut off; therefore additional contacts B and DR ("brakes" and "demagnetizing resistance") are provided on the first power notch; through these contacts a small current is sent through the brakes in the direction opposite to that in which they are usually magnetized. This destroys the residual magnetism and the brakes are released. The corresponding scheme of connections in shown on the extreme right side of the diagram.

There are a few additional points in the general construction of the controller that deserve special mention.

(a) *Mutual interlocking of handles.* The interlocking device is purely mechanical and its construction can be easily followed on the controller itself; its object is:

(1) To prevent reversing the motors while the current is on.

(2) To prevent removal of the reversing handle except in the "off" position.

(3) To prevent moving the regulating handle except when the reversing handle is on "forward" or "backward" (and not in the "off" position).

Make clear for yourself the desirability of this interlocking and what mistakes on the part of the motorman it is intended to prevent.

(b) Another noteworthy feature is the *"blow-out" coil* placed on the bottom of the controller and intended for blowing out the electric arc between the fingers and the drum strips every time the circuit is broken. Its application is based on the fundamental fact that an electric current being placed in a magnetic field tends to move *across* the field, in other words so as to cut the lines of force. The pole pieces of the above coil are placed so that the lines of force are perpendicular to the direction of the arcs and tend to move them outside, increasing their length and finally rupturing them. The blow-out coil is one of the most essential parts of the controller; it must be remembered that the circuits of a street car is broken thousands of times a day, and without a blow-out arrangement the sparks would deteriorate the contacts in a very short time.

It will be noticed that the blow-out coil of our controller consists of two sections, one operative when the power is on, the other when the brakes are applied.

This exercise with the controller should give a fairly good insight into the operation and circuits of electric cars; to get the full benefit the student should come into the laboratory prepared as to the main points and principles involved in this work; then it will not be difficult to trace out the connections of the controller, to connect it to the resistances and to the motors and finally to observe the actual phases of operation.

(c) In order *to prevent the motorman from moving the controller handle too fast* at the start special mechanical devices are sometimes used which limit this speed to a certain predetermined value. A simple apparatus of this kind, the so-called "Automotoneer" will be found in the laboratory near the controller. It is desired that the students familiarize themselves with its construction and operation. It is claimed that considerable economy in power consumption and a better schedule is obtained by using this device, since it limits the rush of current at the start and permits of a more uniform acceleration.

2. *Machine-Tool Controllers.*

Machine-tool controllers are usually called upon to operate only one motor instead of two as in the above described street-car controller. For

this reason machine-tool controllers are much simpler in their construction than railway controllers and their connections can be more easily understood.

An ordinary machine-tool controller has in the most general case to perform the following duties: to start the motor, to reverse the motor and to vary the speed. However complicated the connections inside the controller may be, the machinist does not need to know about them; all he has to do is to turn the handle one way or the other; the controller does the rest.

Motors used for driving machine-tools are mostly shunt wound (in a few cases compound wound). The motor is started with some additional resistance in the armature circuit in order to limit the rush of current; this resistance is gradually cut out as the motor gains speed. Speed is regulated either by varying the field current by means of a resistance in the field circuit, or by varying the pressure at the armature terminals (multi-voltage system). When an exceptionally wide range of speed control is required both methods are used in a combination. To reverse the motor the armature leads are interchanged; the direction of the current in the field circuit remains the same at all times.

Two samples of actual connections in the popular type of a drum-type of machine-tool controller are shown in Figs. 15 and 16. These controllers perform all the above operations; but before attempting to study their connections it is advisable to make clear to oneself more elementary connections shown in Figs. 11, 12, 13 and 14; connections shown in Figs. 15 and 16 are but a combination of these.

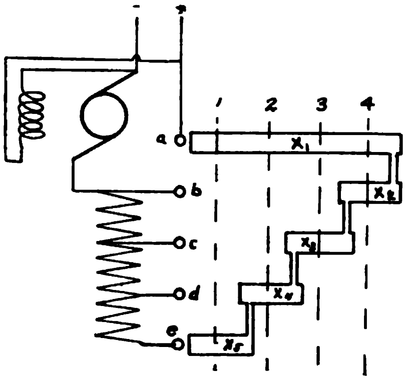


Fig. 11.

In these figures the controller drum is shown as before developed on a plane; different positions of the fingers on the copper strips are indicated by dotted vertical lines. Fig. 11 represents the connections of a controller used for starting only. On the first notch the current from + and the finger *a* passes through the strips x_1, x_2, x_3, x_4 and x_5 to the finger *e*; thence through the whole starting resistance to the armature of the motor and out to the — terminal of the line. On the second notch the finger *d* touches the strip x_4, and part of the starting resistance, that between *d* and *e*, is cut out. On the third notch still more resistance is cut out and finally on the fourth notch the current flows through *a*, x_1, x_2 and *b* direct to the armature without any starting resistance in series; this is the running position of the drum.

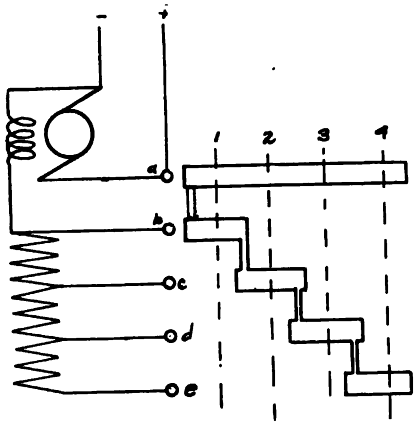


Fig. 12.

Fig. 12 shows controller connections for speed control by means of a variable resistance in the field circuit; for the sake of clearness the starting connections are omitted. On the first notch the field is excited directly across the line without any resistance in series with it. This gives the strongest field and therefore the lowest speed. In the second position the resistance between the fingers *b* and *c* is inserted into the circuit, etc., until on the last notch all of the field resistance is put into the circuit and the motor runs at its highest speed.

Connections for reversing the motor are shown in Fig. 13. When the drum is in the "forward" position the current from + flows through

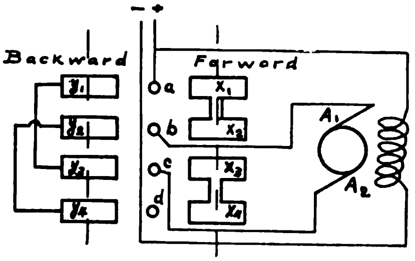


Fig. 13.

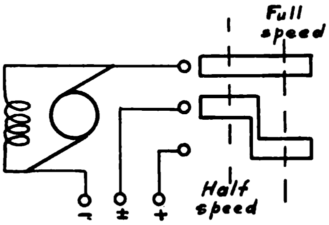


Fig. 14.

a, x_1, x_2 and b to the armature terminal A_1, and returns to — through the terminal A_2. When the controller handle is in the "backward" position the current passes through a, y_1, y_3 and c to the armature terminal A_2 thus flowing through the armature in the opposite direction. Therefore the motor also runs in the opposite direction.

Controller connections for operating a motor on a three-wire system are shown in Fig. 14. In the position marked "half-speed" the armature is connected between the negative and the neutral (±) wires; at full speed it is connected between the + and the — terminals.

With a clear understanding of these simple diagrams, following out the connections in Figs. 15 and 16 will hardly offer any difficulties. Fig. 15 represents a single-voltage reversible controller; the one shown in Fig. 16 is adapted to be used on a three-wire line. The motors shown

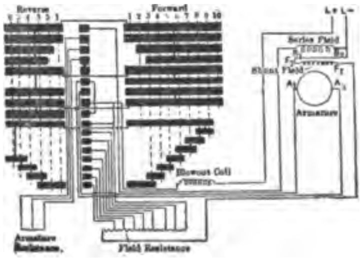


Fig. 15.

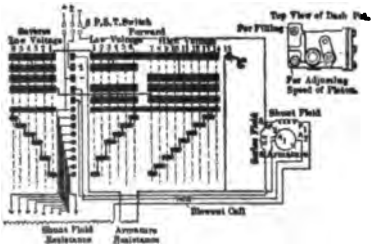


Fig. 16.

are compound-wound, but this has nothing to do with the operation of the controllers, which can just as well be used with simple shunt-wound motors. The blow-out coil shown in both sketches is for the purpose of extinguishing the arc at the finger strip that opens the circuit last. The coil is connected in series with the main circuit and produces

a strong magnetic field in the place where the last contact in the controller is broken. This field shifts the arc outwards, increases its length, and in this way blows it out.

Controller shown in Fig. 15 has two starting positions, 1 and 2, in which the armature resistance is gradually cut out of the circuit; the other positions are for field control. Controller shown in Fig. 16 has no starting notches; its starting resistance is automatically cut out by a spring-actuated contact *c* which is released by the controller and retarded by a dash-pot, shown in the upper right hand corner of the sketch. This arrangement prevents a rush of current due to the operator passing the first few contacts too rapidly.

A special experimental controller is provided in the laboratory, without any connections between the fingers or the drum strips. The students are supposed to wire it up so as to suit certain given requirements. The experiment may be performed in the following order:

(1) Connect up the controller for starting a shunt motor in one direction only, without field control;
(2) Add the necessary connections for regulating the field;
(3) Supplement the scheme for reversing the motor;
(4) Wire up the controller complete for running on three-wire system.

A motor is provided to which the controller can be connected so as to check the wiring by actually running the motor. At the end of the laboratory period all the connections should be taken off and the controller left as found at the beginning of the exercise.

The above controller being an experimental piece of apparatus is not provided with a blow-out coil; in order that the students may study the action of the same a separate electro-magnet is provided, on which the action of the magnetic field on an electric arc can be observed. Connect the coil into a circuit with a resistance in series, and then open the circuit once between the poles of the electromagnet, and then outside of its field. You will notice a marked difference in the behavior of the arc. Reverse the direction of the field or of the current and you will find that the arc is blown out in the opposite direction. In performing the experiment with the blow-out coil the students must be careful to have the wires well insulated. The e. m. f. of self-induction when breaking the circuit may reach several hundred volts and give an unpleasant shock.

The same controller can be wired up as a reversible crane controller to be used with a series-wound motor. On the first notch the armature, the field and all of the starting resistance must be connected in series: then as the motor speeds up the starting resistance is gradually cut out of the circuit. The motor is reversed by reversing either the armature or field leads.

In addition to the above machine-tool controller a few modern motor controlling devices are exhibited in the laboratory for a study of their electrical connections and mechanical features. They comprise:

(1) An unsymmetrical three-wire controller with a separate electrically-operated starting switch (similar to that used in controller Fig. 16).

(2) An "Accelerator", or an electrically operated motor starter, as shown in Fig. 3*a*. This accelerator in conjunction with an electrically operated main switch (Fig. 3*b*) and a reverser can be connected for operating elevator motors. There is also a float switch provided which can be used with the accelerator for automatically starting and stopping motor operated pumps when the water in the main tank is below or above certain limits.

(3) A face-plate crane controller.

(4) An elevator controller with the starting lever driven by the motor itself.

(5) A few motor starting and regulating rheostats with such attachments as to make these rheostats practically fool proof. Some of them have no-voltage release, others have in addition an overload release, thus combining a starter and a circuit breaker in one apparatus. One of the rheostats intended for speed control is arranged so that the motor cannot be started with the field weakened.

All these devices represent the latest American practice in motor controlling apparatus, and they contributed greatly toward making electric motors reliable and popular for all kinds of drive, even where the motor has to be entrusted to incompetent men. Much skill and ingenuity has been exhibited in perfecting these devices, and it is expected that the students will make clear to themselves at least the underlying principles of their construction and operation.

All the necessary diagrams of connections of these controllers will be found in the laboratory, and where they are not given it is expected that the students will trace them out in the apparatus itself.

DIRECT-CURRENT GENERATOR CHARACTERISTICS.

Direct-current generators used for producing current for light and power are either shunt wound or compound wound. In a shunt-wound machine (Fig. 1) there is but one exciting or magnetizing winding; this consists of many turns of a comparatively small wire and is connected across the brushes of the machine, in other words in parallel with the armature winding and with the current consuming devices in the external circuit.

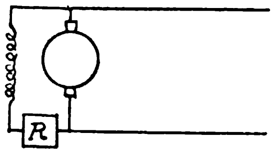


Fig. 1.

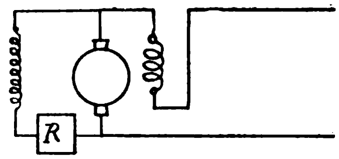


Fig. 2.

The compound-wound generator (Fig. 2) has in addition to a shunt field winding a series field winding, which is connected in series with the armature. The current flowing through this winding automatically strengthens the magnetism of the machine in proportion to the load it is carrying.

One of the most important requirements in practical operation of generators supplying current for light and power is that the voltage must be nearly constant, independent of the load. In other words it means that each customer should get the same quantity and quality of light from his lamps whether there are many or only a few customers using light at the same time.

This condition cannot be strictly fulfilled with a shunt-wound machine, unless there is continuous regulation of the field current by using the field rheostat *R*. Without regulating the voltage drops considerably as the load increases. This is due to the following three causes:

(1) Part of the induced voltage is consumed by the resistance of the armature; this drop *ir* is proportional to the armature current, or practically to the load of the machine.

(2) The armature currents tend to produce a magnetization oppo-

site to that due to the shunt field winding, and in this way weaken the original field. The voltage induced in the armature is therefore correspondingly lower.

(3) As the terminal voltage of the machine decreases because of the two above causes, the current in the shunt winding, which is connected across the terminals, also decreases in the same proportion. This again weakens the field and reduces the voltage still further.

The series winding shown in Fig. 2 tends to strengthen the field as the load increases and counteracts the influence of three above mentioned causes of voltage drop. As the effect of these causes is proportional to the armature current (at least approximately), and as the compensating effect of the series winding is also proportional to the armature current, it becomes evident, that by properly designing this winding, it is possible to counterbalance the voltage drop, so that the machine will give the same voltage at all loads; such machines are sometimes called *flat-compounded.*

By providing more turns in the series winding than is necessary for compensating the voltage drop, the machine can be *over-compounded,* in other words its voltage will be higher the heavier the load. This is frequently done in generators supplying power for electric railways, where it is necessary to compensate for voltage drop in long feeders.

Curves which show the influence of the load or any other factor on the voltage of the machine are called its characteristics. They permit judgment on the behavior of the machine in regard to its voltage fluctuations under various conditions. The purpose of this laboratory exercise is to determine experimentally the characteristics of shunt and compound wound generators.

1. Shunt-wound Generator.

When a shunt-wound generator is running on a variable load the operator usually, from time to time, regulates the voltage by means of the field rheostat in order to keep it fairly constant. In order to see what regulation can be expected under such conditions the students should take two characteristics as corresponding to two extreme cases:

(1) The machine is left *entirely without attention* so that the voltage fluctuates freely with the load.

(2) The switchboard attendant *regulates the field continuously* thus keeping the voltage absolutely constant.

In actual practice an intermediate condition exists: the attendant does not watch the voltmeter all the time, but corrects the voltage from time to time.

In order to take the first curve, so-called *load characteristic*, start the machine, bring it up to full speed, and load it on resistances, regullating these resistances and the field rheostat so as to get the rated voltage of the machine at a load exceeding the rated capacity of the machine by about 25 to 30%. Read amps. load, voltage of the machine, and field current; the speed should be kept as nearly constant as possible throughout the whole test. Now reduce the load somewhat, leaving the field rheostat in the same position as before, in other words allowing the voltage of the machine to fluctuate freely. Read again volts, amperes and field current; then reduce the load again, etc., until all of the load has gradually been taken off the machine.

The same test can be repeated with another setting of the field rheostat, for instance such that the full rated voltage takes place at 100%, or at 75% of full load; it is also desirable to have a third curve corresponding to such a position of the field rheostat, that the machine gives its full rated voltage at a small load, say about 25% of full load or even at no load. In each case after having properly set the rheostat begin with about 25% overload and then gradually reduce the load to zero. The second set of curves, when the excitation is regulated so as to keep the voltage constant (*excitation characteristic*, so-called) is taken in a similar way, except that the setting of the field rheostat is no longer constant. Bring up the load and the voltage so as to have the full rated voltage of the machine at a reasonable overload, say 25%, and then gradually reduce the load, at the same time increasing the resistance in

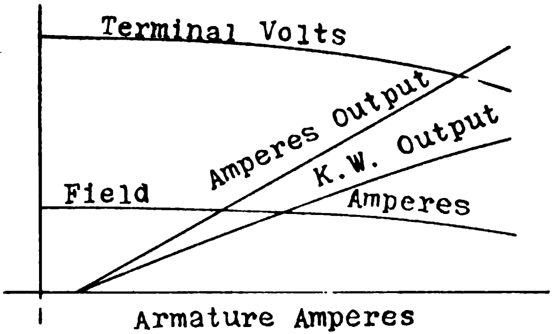


Fig. 3.

the field circuit, so as to keep the voltage constant. Read amperes load and the field current, keeping the speed of the machine constant.

Plot all the above data to armature amperes as abscissae (Fig. 3). The curves for each set of readings should comprise: field current, external load current, terminal voltage and kilowatt load. These curves will give a clear picture of the performance of the machine.

It is interesting to separate the total voltage drop shown in these curves into its three components: ohmic drop, drop caused by the armature reaction, and that caused by the decrease of the field current (Fig. 4). The ohmic drop can be easily calculated by multiplying the armature current by the resistance of the armature (including that of the brushes). The drop due to the decrease in the field current can be found from the curve shown in Fig. 5, the so-called *no-load characteristic*, or

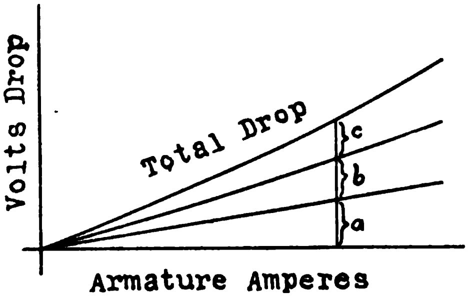


Fig. 4.

a----ohmic drop
b----drop due to increase in field current
c----drop caused by armature reaction,

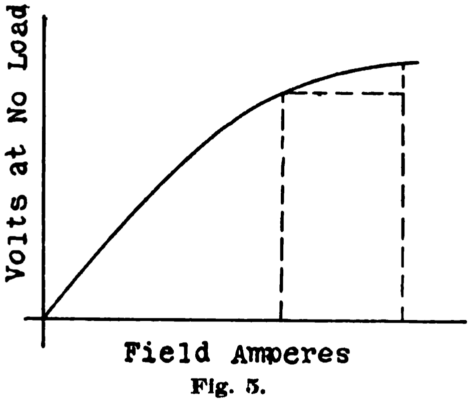


Fig. 5.

the magnetization curve. Knowing from Fig. 3 the values of the field current at no load and at the load under consideration, the corresponding decrease in voltage can be read off on this magnetization curve. Adding the drop due to this cause to the *ir* drop and subtracting the sum from the total drop we find the drop due to the armature reaction. It is required that this analysis be made on at least one of the performance characteristics, and the result plotted as shown in Fig. 4.

This separation of the voltage drop into its components requires a knowledge of the value of the ohmic resistance of the armature, and of the magnetization curve of the machine; therefore a complete test includes this data.

The resistance of the armature is determined by the drop of potential method. A current is passed through the armature from an external source and the voltage at the armature terminals measured with a low-reading voltmeter. The ratio of the voltage to the current gives the resistance of the armature. In performing this measurement it is advisable to hold the voltmeter leads once on the terminals of the machine, and then on the commutator bars, in order to separate the armature resistance proper from that due to the contact resistance at the brushes, and of the resistance of the brushes themselves.

This contact resistance is different when the machine is at rest, from that when the machine is running. To see the difference, the machine can be run at a slow speed with the field circuit open, and the same measurement repeated. It must be remembered, however, that even when the field circuit is open there is some residual magnetism in the field. This magnetism induces some voltage in the armature and considerably vitiates the results. In order to eliminate its influence the measurements must be repeated with the machine running in the opposite direction at exactly the same speed. The average of the two resistances will give the true resistance of the armature.

It must also be remembered that the resistance of copper changes by about 1% for each 2.5°C., so that in giving the results it is necessary to state to which temperature they refer. The resistance of the armature, and therefore the voltage drop is somewhat higher when the machine is hot. In contracts and guarantees it is usually stated that voltage drop and efficiency must not be below a certain figure when the temperature of the machine is say 50°C. above ordinary room temperature.

The no-load or magnetization curve is taken by running the machine

at normal speed and no load, with various field currents. Voltages plotted to field amperes as abscissae give the magnetization curve. Its name is derived from the fact that the voltages induced at no load, are proportional to the magnetic flux of the machine, so that to another scale the same curve gives the effective magnetic flux of the machine as a function of the exciting ampere turns. Strictly speaking the machine is not running at no-load, when it has to excite itself, but the excitation load is so small that for all ordinary purposes the machine can be assumed as carrying no load. If a greater accuracy is required, the machine can be run at strictly no load, excited from a separate source.

The experiment should be preferably conducted in the following order:

(1) Take a load characteristic corresponding to a full rated voltage at 25% overload.

(2) Take an excitation characteristic under the same initial conditions as (1).

(3) Take the magnetization (no-load) curve.

(4) Measure the resistances of the armature and the field.

(5) If time allows, take one or more load characteristics, with rated voltages at 100, 75, 50, 25% of full load, and at no load.

The report must comprise:

(a) The results of the runs (1), (2) and (5), plotted to armature amperes as abscissae. Plot field current, external load current, terminal voltage and kilowatts load.

(b) The magnetization curve of the machine.

(c) Resistances of the armature and the field.

(d) Separation of the total voltage drop into its three components; this should be done for one of the load characteristics.

NOTE. In most text-books it is stated that voltage drop in shunt-wound generators is caused by *two* factors: ohmic drop in the armature, and the armature reaction. This is true so long as the machine is separately excited or else the exciting current is kept constant. In the actual operation of the machines, however, the exciting current itself varies with the terminal voltage of the machine, so that in predetermining the voltage drop of a machine *left to itself* without regulation, this third cause must also be considered.

When making a special study of the armature reaction the experiment can be arranged so as to eliminate the influence of the varying

field current. The field current can be kept constant from no load to full-load by means of the field rheostat. In this case the voltage drop will be caused by *two* factors only: ohmic drop and armature reaction. Subtracting the former we readily find the magnitude of the armature reaction, for a given load and excitation. If desired, one of the load curves on the machine can be taken with a constant field current, and the influence of the armature reaction determined in this way.

2. *Effect of Compounding.*

As was explained before the purpose of the series or compound winding is to compensate for the voltage drop in the machine and to make its terminal voltage constant, independent of the load.

In many cases, particularly in railway generators, the machine has to be *over-compounded,* that is to say, it is expected to give a higher voltage the heavier the load. This is to compensate for voltage drop in long feeders and to give a more constant pressure on the trolley wire. Suppose, for instance, that the drop in a feeder at full load is 50 volts; the generator voltage has to be 550 v. in order to give the standard voltage of 500 v. on the trolley wire. At half load the drop in the feeder is only 25 v. and the generator voltage must be 525 v. in order to give the same pressure on the trolley wire. Finally, at very small loads the drop in the feeder is negligible and the generator pressure must be about 500 v. Thus the curve of generator pressure should be a straight line ascending with the current.

The generator can be overcompounded to any desired degree simply by putting on more turns of series winding than is necessary for merely compensating for the armature reaction and ohmic drop in the machine itself. The rest of the ampere turns will raise the voltage in proportion to the load.

It is difficult to design a machine with a right number of series turns for compounding or over-compounding. The permeability of iron may be somewhat different from that admitted in the calculations; the armature reaction cannot be predetermined with a sufficient accuracy, and finally, different customers may desire the same type of machine with a different degree of over-compounding and it would not pay to separately design and manufacture the series winding for each case. Therefore large modern generators are usually provided with a number of compounding turns sufficient for a reasonably high degree of over-compounding, and if a smaller degree is needed the *compound winding is shunted*

by German silver strips (Fig. 6), so that only part of the total current flows through the series field. In this way magnetizing action is reduced,

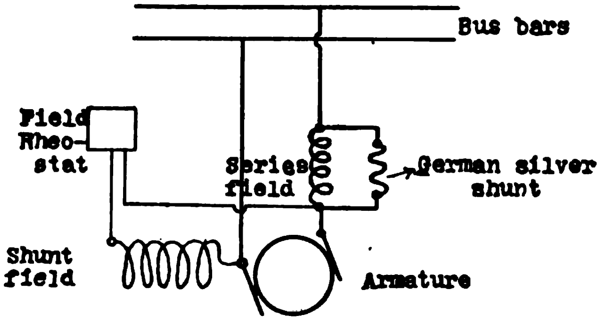


Fig. 6.

and by varying the resistance of the shunt any degree of compounding can be easily obtained without changing anything in the machine itself.

The shunt winding of compound-wound generators can be connected either across the armature (short shunt, Fig. 6), or across the terminals of the machine (long shunt, Fig. 7). There is not much difference between these two types and both are used in practice.

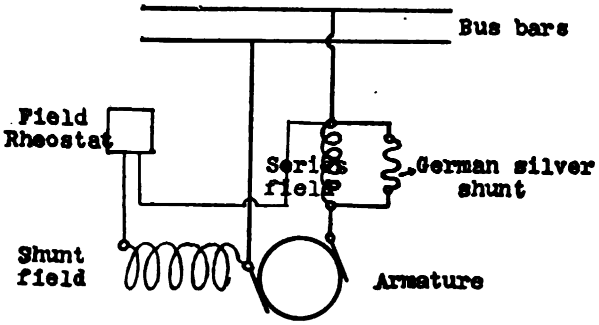


Fig. 7.

In adjusting German silver shunt around a series winding, it must be remembered that the speed of the prime mover, whether it be a steam engine, a water wheel or a gas engine, is not constant between no load and full load, and with some types of engines the drop of speed at full load may be considerable. Therefore, a generator adjusted on the testing

floor while being driven by an electric motor at a constant speed may not give the required degree of compounding when installed in the power house. The same may occur when the machine is intended to be driven by an induction motor, which has a lower speed at full load than at no-load. In any case in order to adjust the compounding winding properly, the speed characteristics of the driving motor or the prime mover must be known.

The machine used by the students for this exercise is a shunt-wound generator and they are supposed to provide it with a compound winding. The necessary number of turns can be determined either by successive trials or, still better, by the following experiment: Suppose the machine under test to be a 110 v. 220 amp. shunt-wound generator; first determine the value of the field current that gives the rated voltage at no-load, then same at full load. For instance, let the machine give 110 v. at no load at a field current of 5.5 amp.; when the load is put on, the voltage naturally drops, and in order to raise it to 110 v. the field excitation must be increased by say 6.0 amps. Let the total number of turns on the shunt winding be 2400; then the difference $(6\text{-}1 - 5.5) \times 2400 = 1440$ amp.-turns, represents the additional excitation necessary for compensating for armature reaction and ohmic drop in the armature. As this number of ampere turns is to be supplied by the series winding at full load current of 200 amps., the number of turns has to be about 8, because $200 \times 8 = 1600$ amp. turns. This is somewhat more than necessary, but an allowance has to be made to compensate for the ohmic drop in the compounding winding itself. If the number of turns of the shunt winding is not known from the design data of the machine, it can be easily determined by exciting the machine separately by a known number of ampere-turns and comparing the voltage it gives with that given by self-excitation. For instance, if it takes 72 turns of an auxiliary winding at a current of 100 amp. to excite the machine up to say 50 v., while it takes only 3 amps to do the same by using the shunt winding, then the number of turns of the shunt winding is evidently

$$\frac{100 \times 72}{3} = 2400 \text{ turns}$$

Having thus determined the necessary number of turns of the series winding, same should be put on the machine and the total load characteristic of the machine taken in order to verify the above calculations and to see what voltages the machine gives at partial loads.

Suppose the machine to be compounded so as to give the same voltage at full load as at no-load; the voltages at partial loads will be somewhat higher than is necessary. This is caused by the magnetic flux of the machine not being proportional to the number of exciting ampere turns; commercial machines are designed with such a degree of saturation in the iron constituting the magnetic circuits that this circumstance is more or less noticeable. In many cases this rise in voltage above normal at partial loads is of no consequence; if an exact compounding is required a little regulation of the field rheostat by hand becomes necessary.

The students should try to over-compound the machine so that it would give from 5 to 10 per cent higher voltage at full load than at no load. With the same data as before, suppose the machine to give the right voltage (110 v.) at full load, with 8 turns of compounding winding and with the same field current of 5.5 amps. as at no load. The requirement is now to put on more turns of compounding winding in order to get 116 v. at full load. To determine this additional number of turns experimentally, we over-excite the shunt field until we get 116 v. at the terminals of the machine. Let the necessary field current now be 6.2 amps., which corresponds to an additional excitation of $(6.2 - 5.5) \times 2400 = 1680$ amp.-turns. Not all of this excitation, however, needs to be supplied by the compounding winding, because with the higher terminal voltage the shunt current increases automatically; in our case it will be $\frac{116}{110} \times 5.5 = 5.8$ amps., which means an increase of $(5.8 - 5.5) \times 2400 = 720$ amp.-turns; the rest, $1680 - 720 = 960$ amp.-turns must be supplied by the series winding. With a current of 200 amps., 5 or 6 turns will be sufficient to bring about the desired overcompounding (in addition to 8 turns put on before).

Having thus over-compounded the machine the students should put some German silver resistance around the compounding winding and adjust this resistance so that the machine be again flat-compounded. This will illustrate the case where it is desired to use a machine at a smaller degree of over-compounding than it was originally designed.

The experiment can be conveniently conducted as follows:

(1) Take a load characteristic of the machine, using it as a shunt generator, that is to say without the compounding winding. Set the

field rheostat so as to get the rated voltage at no load, and then keep it in this position gradually increasing the load to say 25% overload. Note the voltage drop with the increasing load. This run is intended to give an idea of what the regulation of the machine would be without the series winding.

(2) Set the field rheostat and the load resistances so as to get full rated load current at normal voltage (the same as you had before at no-load). Note the increase in field current necessary for this.

(3) Now determine the number of turns in the shunt winding. To do this first take a magnetization curve of the machine using the shunt winding only. Then put a *known* number of series turns on the field magnets of the machine, and take the same no-load characteristics, having the machine separately excited through this series field. The shunt winding must in this case be kept open. The comparison of the exciting currents in both cases will permit the determination of the number of turns in the shunt winding as explained above on p. 115.

(4) From the results of (2) and (3) figure out the necessary number of series turns for flat compounding and place them on the machine.

(5) Check the results by taking the load characteristics using both shunt and series windings.

(6) Determine the number of series turns for overcompounding the machine by about 10%, and check the results experimentally.

(7) Shunt the series winding by a German Silver strip and adjust it so as to make the machine flat-compounded again.

The requirements for the report are as follows:

(1) Plot the load characteristics, as explained in the note on Shunt-Wound Generator, with and without compounding winding; also for overcompounding if sufficient data was taken in the laboratory.

(2) Plot no-load characteristics obtained by using the shunt winding only and the series turns only; explain how the number of turns in the shunt winding was determined from these two curves and give the numerical results.

(3) Explain how the number of turns of the series winding was predetermined for flat compounding and for overcompounding.

SHUNT MOTOR.

One of the most important things for the manufacturer and the user of a motor to know is its efficiency, and the variation of the same with the load. Efficiency by definition is the ratio,

$$\frac{output}{input},$$

or, since the output is equal to the input less the losses in the motor, efficiency can also be represented as the ratio,

$$\frac{input - losses}{input}.$$

These two expressions for the efficiency, though identical in principle, give two distinct methods for experimental determination of the efficiency of a motor. According to the first expression, both input and output have to be measured; according to the second expression only the losses must be determined experimentally, as a function of the input. In the first case the motor must be actually loaded either by means of a brake, or on another machine whose efficiency has been previously determined. In the second case the losses can be determined at no load, and with some assumptions can be predetermined on all other loads.

The first method is sometimes called *the direct method* for determining the efficiency of a motor, the second one—*the indirect.* Both methods are used in practice, and there are cases where either one or the other is preferable. Take for instance the case where a manufacturing company has to show a prospective buyer the efficiency of a small motor of their make, and suppose that the customer is not well posted on the theory of losses in electrical machinery. The only convincing test for him would be to put a Prony brake on the motor, read the input and the output and take their ratio.

With a small motor there is no objection to using this method; but if the motor is a 500 hp machine and must be tested up to say 50% overload, the proposition is a different one. The difficulty in providing a

suitable brake, and the expenditure of power involved, are such that the indirect method is practically the only one that could be used. Between these two extreme cases there are all others in which the direct or the indirect method is selected according to the circumstances and the personal views of the engineer who has to decide the question.

The two laboratory experiments described here are intended to illustrate both methods of determining the efficiency, in application to a shunt-wound motor.

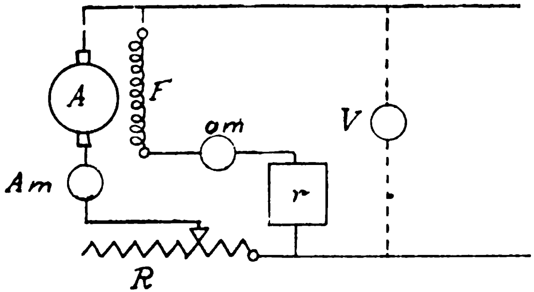


Fig. 1.

There are two types of direct-current motors commonly used in practice: shunt-wound motor (Fig. 1), and series-wound motor (Fig. 2). In a shunt-wound motor the field winding is connected directly across the supply circuit, so that the magnetism of the motor is practically

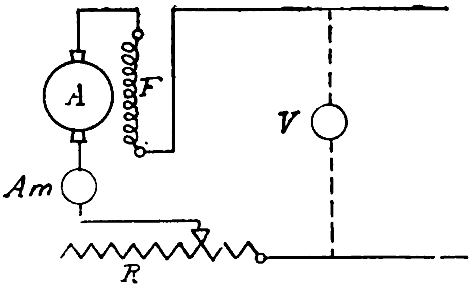


Fig. 2.

constant at all loads. In a series-wound motor, the field winding is in series with the armature circuit; as the load increases the current taken by the motor also increases and this increased current strengthens the magnetic field of the motor.

There is a marked difference in the performance of these two types of motors, so that each type has a field of application of its own. The shunt motor is essentially a constant speed motor, while the speed of the series wound motor increases as the load decreases. A theoretical explanation for this is given in the Appendix to this article; at any rate this is a fact observed experimentally. Shunt-wound motors are used for machine-tool drive, and for driving various machines in textile and other industries, where a constant or nearly constant speed independent of the load is required. Series-wound motors are used in railway, crane and hoisting work, where a heavy starting torque is necessary and where the motors have to be frequently started and stopped. In these cases it is desirable to have a motor which automatically slows down as the load increases, in order not to have too large fluctuation in power demand.

For an efficiency test on series-wound motor see the article on "Series Motor."

1. Brake test.

A Prony brake is the simplest device used for loading small and moderate size motors; it is so commonly known that it seems hardly necessary to give here any directions for using it. Particular attention should be paid to keeping the load constant, while the speed is measured. If P is the net pressure on the scale, at the end of a lever l feet long, the pressure at the end of a lever *1* foot long is Pl lbs.; consequently the work in ft.-lbs. performed during one minute is $Pl.2\pi n$, when n is the number of revolutions of the motor per min. The same in hp. is

$$\frac{Pl.\,2\,\pi\,n}{33000},$$

or

$$h.p. = \frac{P\,l\,n}{5252}.$$

This is the common expression for figuring out the output of a motor from a Prony brake test.

The motor must be wired up as shown in Fig. 1; one independent circuit comprises the field winding F with its regulating rheostat r and an ammeter am; the other circuit is formed through the armature A of the motor with its starting rheostat R and an ammeter Am. If the voltage of the line is not sufficiently constant it is advisable to have another regulating rheostat either in the armature circuit or on the line

so as to keep the voltage at the motor terminals as nearly constant as possible (*). A voltmeter *V* is connected across the terminals of the machine for measuring the pressure at which the machine operates and for keeping it constant.

Before beginning the test it is advisable to let the motor run idle for about half an hour or so, in order to get the bearings warmed up and the friction more constant. This may not be practicable in the laboratory because of the loss of time that would occur; but it is mentioned here as a precaution advisable in more accurate work.

Begin the brake test with the highest load, say 25% overload; read armature amperes, field amperes, terminal voltage, speed, and brake load. Then gradually reduce the load to zero, taking a sufficient number of readings (from 8 to 10) for plotting a curve. The field current and the terminal voltage must be kept constant throughout the whole test. Plot to hp. output as abscissae; hp. input, efficiency, speed and torque.

It was mentioned before that a shunt motor was a constant speed motor; this is true so long as the field current and the voltage at the motor terminals are kept constant. The speed can, however, be varied at will by regulating either of these or both. Reducing the armature voltage alone reduces the speed in the same proportion; decreasing the field current increases the speed (see Appendix). A study of the practical use of these means for speed control is taken up in another laboratory exercise (Variable-speed electric drive); here it is only desired to call attention of the students to these two methods of regulating speed of shunt wound motors.

For this purpose repeat the above brake test with a field current say 10% lower than before (**), and then again with the armature voltage about 20% below normal. Plot similar curves for these two runs and compare them to those plotted for the motor operating under normal conditions of field strength and voltage.

(*) Ordinary commercial starting boxes are not intended to be used for voltage regulation, and should never be used for this purpose. An inspection of such a rheostat will show why this is so.

(* *) It is not advisable to go too far with lowering the field, since the speed will become too high, and moreover the motor will spark excessively, unless it is especially designed for variable-speed work.

2. *Efficiency from losses.*

The losses in an electric machine whether running as a motor or as a generator can be subdivided into three different classes:

(a) *Copper loss* (I^2R) in the armature and field circuits.

(b) *Iron loss* (hysteresis and eddy currents) in the armature core;

(c) *Mechanical losses:* bearing and brush friction, and windage (air resistance).

The copper losses need not be determined experimentally; it is only necessary to measure the ohmic resistances of the corresponding windings, then the I^2R can be calculated for any value of the current.

The iron loss depends on the magnetic flux of the motor and on its speed. In a shunt-wound motor the flux is constant so long as the field current is constant; the speed is also approximately the same at all loads; therefore the iron loss in a shunt-wound motor is approximately constant.

The brush friction and the windage loss depend on speed only, and consequently can also be assumed nearly constant. The bearing friction is also constant in a direct-connected motor, but when the motor is used for belt drive the friction evidently depends on the tension of the belt. This increase in friction could hardly be predetermined, and it is customary not to charge it to the motor.

Thus the items (b) and (c), viz., iron loss and friction in a shunt motor can be assumed nearly constant at all loads and having the same value as when the motor is running at no load. This gives a convenient method for measuring these losses; all that is necessary is to measure the power that the motor armature takes when running at no load. This input is all converted into iron loss and friction, with the exception of a small part of it which is necessary for supplying the I^2R loss in the armature winding and the brushes. This correction is usually negligeable, but if necessary can be readily applied as the resistance R is known, or at any rate must be measured for figuring out the efficiency of the motor.

Suppose, for example, the efficiency of a 50 H.P. 220 v. motor is to be determined. It was found that at no-load the motor takes 10.6 amp. (armature current), and the field current at which the motor is supposed to run is equal to 5.8 amp. The resistance of the armature was measured to be 0.0377 ohm. We have: no-load losses neglecting copper losses (iron loss and friction) $= 220 \times 10.6 = 2.33$ K.W.; excitation loss $= 220 \times$

5.8 = 1.275 K.W.; total losses independent of the load = 2.33 + 1.275 = 3.605 K.W. The loss that depends on the load is copper loss in the armature; and as we do not know what current the motor would take at an output of 50 H.P., we have to find it by trials, or still better, to construct the whole efficiency curve from no-load to say one and a quarter load and then take from this curve the point corresponding to full load.

An ideal 50 H.P. motor would take at full-load

$$\frac{50 \times 746}{220} = 170 \text{ amp.};$$

the real motor will probably take 190 or 200 amp. Therefore we construct the efficiency curve for points between say 50 amp. and 250 amperes; then we can be sure that the full-load point lies on this curve. Take for instance the 150 amp. point. Total electrical input = $(150 + 5.8) \times 220 = 34.28$ K.W.; copper loss in the armature = $150^2 \times 0.0377 = 0.848$ K.W.; total loss = $3.605 + 0.848 = 4.453$ K.W. The efficiency is $\frac{34.28 - 4.453}{34.28} = 87\%$ and the output $= \frac{34.28 - 4.453}{0.746} = 40.1$ H.P. In this way, efficiency can be found for various values of output; and the efficiency corresponding to an output of 50 H.P. found from the curve plotted.

This method of figuring out efficiency from the losses is not quite correct, because it is assumed that the speed remains constant at all loads. While this is approximately true, still the load speed in some motors may drop a few per cent between no-load and full load. In order to take this into account the no-load run can be supplemented by the so-called *speed characteristics.* The motor is connected to a dynamo, a blower, or in fact to any convenient machine capable of absorbing power, and is run from no load to the maximum load which it is supposed to carry. The field current and the voltage are kept constant; armature amperes and speed are read for various loads, and the speed curve is plotted to amperes as abscissae. Now the no-load test can be run within the limits of the speeds of the motor, and in figuring out the efficiency the value of the iron loss and friction taken for the speed corresponding to a given amperes input.

If the motor is expected to be run at higher speeds, that is to say with a weakened field, the ampere-speed curve and the no-load losses must be determined separately for each value of the field current for which the efficiency curve is desired.

The speed variation with the load is determined by two causes: ohmic drop in the armature and the armature reaction. The value of the armature reaction depends on the position of the brushes; therefore the speed of the motor can be varied within certain limits by merely shifting the brushes. Of course no considerable speed variation can be obtained by this means, since the motor begins to spark as soon as the brushes are shifted too far either way from their right position, but this is a convenient method for adjusting the speed to an exact value after an approximately right speed has been reached by the regulating rheostats.

Take a few ampere-speed curves with different settings of the brushes both in leading and lagging positions with respect to the neutral. The position of the brushes is usually referred to as being so and so many commutator bars from the neutral. Then knowing the number of bars in the commutator the angle of displacement can be calculated in degrees. Compare these curves in regard to the power input for the same load (in other words the efficiencies at the same load) with different positions of the brushes; see if the position at which the speed variation is the least is also the position of maximum efficiency (minimum input).

Take two curves: one with brushes in the neutral, the other with the brushes shifted by a certain number of bars. Take two other speed curves with the same setting of brushes, but with the field weakened. See in which case the shifting of the brushes affected the speed more: with a strong field or with the field weakened. Give an explanation for the observed results.

The armature reaction affects not only the speed of the motor, but its iron loss as well. The armature reacts on the field so as to weaken or to strengthen it (according to the position of the brushes) and moreover distorts it, making it stronger near one end of the pole piece and weaker at the opposite end. Thus with the same field current the actual magnetic flux is different in a loaded machine from what it is at no load; this naturally affects the iron loss which depends on the flux density in different parts of the magnetic circuit. The result is that the actual efficiency of a machine under load is somewhat lower than the one calculated from the losses.

There has been a good deal written on this subject of the increase of iron loss with the load, but as no simple practical rules are available for taking into account this additional iron loss, it is usually left without

consideration. The error committed is very small unless the machine is of a very poor design and the armature reaction has abnormal proportions. Compensating poles or various types of compensating winding for neutralizing armature reaction are coming more and more into use; in such compensated motors the iron loss is the same at no load as with the motor loaded, and no further correction is necessary.*

The laboratory experiment on efficiency from losses can be conveniently arranged as follows:

(1) Belt the motor to a dynamo or a blower and take three ampere-speed curves: with full field, and with the field weakened say 5 and 10%, or more according to what the motor can stand without vicious sparking. Always begin the curve at the heaviest load and gradually reduce the load to zero, the last reading being taken with the belt off. Have the brushes set so as to have the best commutation at full load and then leave them in this position for the rest of the curve.

(2) Repeat the runs (1) with different positions of the brushes.

(3) Run the motor at no load for the values of the field current and within the limits of the speed corresponding to the curves taken under (1) and (2). It is advisable to run the motor within somewhat wider limits of the speed than is necessary in order to better see the shape of the loss curve. During the no-load runs the brushes must be set on the neutral.

(4) Measure the ohmic resistance of the armature, including the brushes.

Your report should contain the following items:

(a) All the ampere-speed curves with necessary explanations.

(b) Iron-loss and friction curves plotted to speed as abscissae for various values of field current.

(c) The predetermined performance curves for at least one value of the field current. These curves should be plotted in the same way as those obtained from the brake test (see p. 121 above).

(*) The above described method of determining efficiency from the losses is equally well applicable to the machine running as generator; the formula for the efficiency is in this case:

$$\frac{\textit{electrical output}}{\textit{electrical output} + \textit{losses}}$$

APPENDIX.

The difference in the behavior of shunt and series wound motors under various loads can be explained as follows: When the armature of a motor revolves, a counter-electromotive force is induced in it by the magnetic field of the machine. This e. m. f., e, is smaller than the applied voltage E by the amount of the ohmic drop IR in the armature and brushes, or

$$e = E - I\,R.$$

In all commercial motors the term IR is equal to but a very few per cent of E, in order to keep the efficiency of the motor sufficiently high; therefor *e is approximately equal to E.* In other words the counter electromotive force induced in the armature is approximately equal to the applied voltage. On the other hand this counter e. m. f. according to the fundamental law of induction is proportional to the magnetic flux and to the speed at which the armature conductors cut the flux. Thus

$$e = C.Nn.$$

where C is a constant, N is the useful flux of the machine and n is its speed. The e. m. f. e being approximately constant so long as the voltage at the armature terminals is constant, the product flux times speed in this formula must thus be constant.

In a shunt-wound motor (Fig. 1) the fields are separately excited so that the flux *is* constant, and does not depend on the load. Therefore the speed of such motors is also approximately constant. When the field current is reduced, this reduces the flux, and according to the above equation the speed must increase to give the same constant e. When the field current is reduced the counter e. m. f. is also reduced the first moment; this causes a rush of current into the armature and an excess of power above that necessary for carrying the load. This excess of power accelerates the motor until the counter e. m. f. has increased sufficiently to allow but the normal current to flow through the armature.

In series-wound motors (Fig. 2) the field strength depends entirely on the load, since the exciting winding is connected in series with the main circuit. Therefore, as the load decreases and the motor begins to

consume less power, a smaller current flows through the field winding; as was explained above, the weaker the field the higher must be the speed. This is the reason why a series motor runs faster the lighter the load. A series motor should never be connected to the supply without any load; it will run away, unless a sufficient resistance is connected in its circuit.

Series motors give a heavy starting torque so important in railway work. This is due to the heavy starting current magnetizing the fields practically up to the saturation limit of the iron. In a shunt motor the field at start is not stronger than under ordinary running conditions. The torque of a motor is proportional to the product magnetic flux times armature current; therefore the series motor, in which both the armature current and the flux increase simultaneously must give under equal circumstances a heavier torque than the shunt-wound motor.

SERIES MOTOR.

The purpose of this laboratory exercise is similar to that described in the Note on Shunt Motors, namely, to illustrate the two methods of determining the efficiency of a series motor:—brake test and efficiency from losses. For general consideration in regard to these two methods and also for a comparison between the series motor and the shunt motor the student is referred to the above note and its Appendix. Here only the tests themselves are described in so far as they offer some distinctive features as compared to those on a shunt motor.

1. Brake Test.

The motor is wired up in series with starting and regulating rheostats and an ammeter. A voltmeter is connected across the motor terminals and the voltage should be kept as nearly constant as possible. Begin the test as usual with the highest load. Take readings of amperes, volts, speed and torque. Then reduce the load by approximately equal steps until the safe limit of the motor speed is reached.

Here is a distinctive difference between the brake test of a shunt motor and of a series motor. With a shunt motor the brake can be safely released, since the speed of the motor is practically the same at no load as when loaded. In a series motor the speed increases enormously as soon as the load is taken off, and either the armature or the commutator or the bearings are sure to be damaged if the motor be allowed to run at this speed. For this reason *always open the circuit before you release* the brake, or at least have sufficient resistance inserted into the circuit to keep down the speed.

As an additional precaution against the motor running away an *underload circuit-breaker* is connected into the circuit; when the load and consequently the current are below a certain limit this device automatically opens the circuit. The students should not, however, rely absolutely on this circuit-breaker. It may "stick" just when it is necessary for it to act. It is best to have one man of the section stand always within reach of the main switch and open the circuit if the motor reaches a dangerous speed.

The speed of the series motor can be regulated either by inserting

a resistance in series with it, or by shunting the field winding by a comparatively high resistance. The first method is the one used on street cars, on cranes and generally where a variable-speed intermittent service is required. This is not an economical method, and, moreover rheostats that can carry heavy currents for a considerable length of time are bulky and expensive. By shunting a part of the current around the field it is weakened and the speed of the motor accordingly increases. This method is preferable when it is desired to run the motor above normal speed for a considerable length of time. (*)Shunting the fields is also a handy means for adapting an old or second-hand motor to a service for which it was not primarily intended.

If a series motor has normally too high a speed, the armature must be shunted instead of the field, so as to make the field current relatively stronger. This method is objectionable since it involves a considerable loss of energy.

Both shunting the field and shunting the armature are good expedients in the hands of a designer for predetermining the performance of a new motor from the results of tests of an existing motor. He can predict what he can get by using the same frame and putting more or less field turns and a stronger or weaker armature, and whether or not he should change the dimensions of the frame so as to get the desired results.

In order to have an idea as to how shunting the field or the armature affects the behavior of the motor, repeat the above brake test with the fields weakened say by 10 and 20%, and then with the armature weakened by similar amounts.

In your report plot all the curves to hp output as abscissae. If possible plot on the same sheet, the data referring to all the five tests, say using different colored ink. Or else plot all the efficiency curves on one sheet, all input curves on another, etc.

The curves should comprise: efficiency, speed, amps. and watts input, and lbs. torque.

(*) The method of shunting fields has been used to some extent on street-car motors, where the car had to run on long level stretches. This expedient has been abandoned because weakening the fields increases the effect of armature reaction and the motors spark. Compensated railway motors are now coming into use, in which the armature reaction is overcome. There is no doubt that the method of shunting fields will now come into use again, especially on interurban roads, where considerable time can be saved by running long stretches at high speed.

It is of interest to separate copper loss in the motor from the other losses (iron loss and friction). The resistances of the series field and of the armature can be easily measured by the drop of potential method and I^2R loss calculated. The rest of the difference between the input and the output represents iron loss and friction. The two losses should be plotted separately, also to hp as abscissae, so as to see their relative importance at various loads.

This is not the best method for measuring iron loss and friction, because a small error in measuring input or output appreciably influences the results; a better method is described below, the next exercise being arranged specially for studying the various losses in a series motor. Still it is desired that the student should separate the losses from the results of the brake test, because this will give him a general idea of the magnitude of these losses and of their variation with load.

2. *Efficiency from losses.*

It is explained in the Note on "Shunt Motor-Efficiency from Losses," that the losses in a direct-current motor, whether shunt-wound or series-wound, consist of copper loss RI^2, iron loss in the armature core and mechanical losses (friction and windage). The copper loss can be easily calculated for any value of the input current if the ohmic resistances of the windings are known. Iron loss and friction can be measured by running the motor at no load, since in this case the whole input into the armature (with a small correction for copper loss) represents the iron loss and friction.

In a shunt motor this method of determining iron loss and friction offers no difficulties, since the speed is nearly constant and the losses are approximately the same at no load as at any other load. It is entirely different with a series motor, because here the speed at no load is many times higher than at full load; moreover, in the series wound motor the field strength and consequently the iron loss depend on the speed and on the load, and these vary within wide limits. Therefore even if it were possible to run a series motor at no load the results obtained would be of no use at any other load.

This can be remedied by separately exciting the motor and varying its field strength independently of the speed, which latter can be regulated by a rheostat in the armature circuit. By this method the series motor is really converted into a shunt motor, and iron loss and friction can be

determined as explained in the above mentioned Note on the shunt motor.

Such a test could be run as follows: Excite the fields separately up to the highest limit of current which the motor is supposed to carry in regular operation. Apply a low voltage to the armature and bring it up to full speed by increasing this voltage. Measure the input into the armature, which input when corrected for slight I^2R loss, is equal to iron loss and friction at this particular speed and field current. Then gradually introduce resistance into the armature circuit, at the same time keeping the field current constant. Read input into the armature at various speeds and plot a curve giving the value of iron loss and friction as a function of speed, for a constant field current. Then repeat the whole test with other values of the field current. A set of such curves will give the value of iron loss and friction for any speed and any value of armature current. Now having in addition to these data an ampere-speed curve of the motor, its efficiency can be easily calculated at any load and speed.

This would be a repetition of the test made on the shunt motor; the method can be somewhat modified, so as to make it more adapted for series motor. This modification also makes possible the separation of the iron loss from the friction, which feature makes the method the more desirable, particularly for a designer.

The method in question consists in making two series of runs at no load; one for determining iron loss and friction *together;* another one in which iron loss is negligeable; in this way iron loss can be separated from the frictional losses.

For the first series of runs the armature of the motor is connected in series with the fields as in actual operation, but is shunted around by a variable resistance. A suitable regulating rheostat is also inserted into the main circuit. In this way the field and the armature currents can be regulated at will either together or separately. The motor is run at no load, so that the input into the armature represents as before the sum of iron loss and friction. (*)

These losses depend on two independent variables; field current and speed. As the speed with a given field is proportional to the voltage

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(*) Having a resistance in parallel with the armature permits of having a strong field even with a small armature current; in this way the speed of the motor is kept within reasonable limits at no load and the normal voltage.

at the armature terminals it can finally be said that *iron loss and friction depend on the field current and the voltage at the armature terminals.* In order to plot curves one of the variables must be kept constant during each run.

It is convenient to keep the armature voltage constant for each curve and to vary the field current by means of the two above mentioned rheostats. Several curves should be taken within as wide limits of armature voltages and field currents as possible.

The second series of runs is intended to give a curve of friction; this is done by simply connecting the armature and the field of the motor in series and running at no-load. The voltage at the motor terminals must be kept sufficiently low; otherwise the motor will run away. The motor takes very little current when running at no-load; therefore its field is so weak that iron loss can be neglected and the whole input into the armature assumed to be equal to the friction loss. Note that this procedure could not be used for shunt motors, because there the field has its full value at no-load as well as at any other load, and iron loss is not negligible under any circumstances.

Subtracting the values of friction obtained from this curve from the ordinates of the previously taken curves, curves can be plotted giving iron loss separately as a function of speed and field excitation. After the above tests the motor must be belted to a dynamo or to any other machine capable of absorbing power, and an ampere-speed curve taken at the normal voltage. Finally the resistances of the armature and the field windings must be measured, thus completing the data necessary for calculating the efficiency from the losses.

The report should contain:

(a) Curves showing separately iron loss and friction for various speeds and different values of the field current.

(b) Ampere-speed curve (load curve) at the normal voltage.

(c) Curves giving the calculated efficiency, input and torque; also the speed curve taken experimentally, all plotted to hp output as abscissae.

(d) Watts copper loss in the field and in the armature, iron loss and friction; also curves giving the same losses in per cent of the input into the motor, all plotted to hp output.

INDUCTION MOTOR—BRAKE TEST.

The induction motor is the most popular type of alternating-current motors, and finds a wide field of application. Its action is based on the principle of the revolving magnetic field produced by two or three alternating currents displaced in phase relative to each other. Such currents are supplied by so-called poly-phase electric generators; two and three phase systems are those in most general use, and, accordingly, induction motors are usually wound for two or three phase circuits.(*)

This exercise is a study of the general performance of a three-phase induction motor, particularly its efficiency, speed-torque characteristic and the power-factor curves. This test will also give the students an opportunity to learn how to handle and to operate this class of motors.

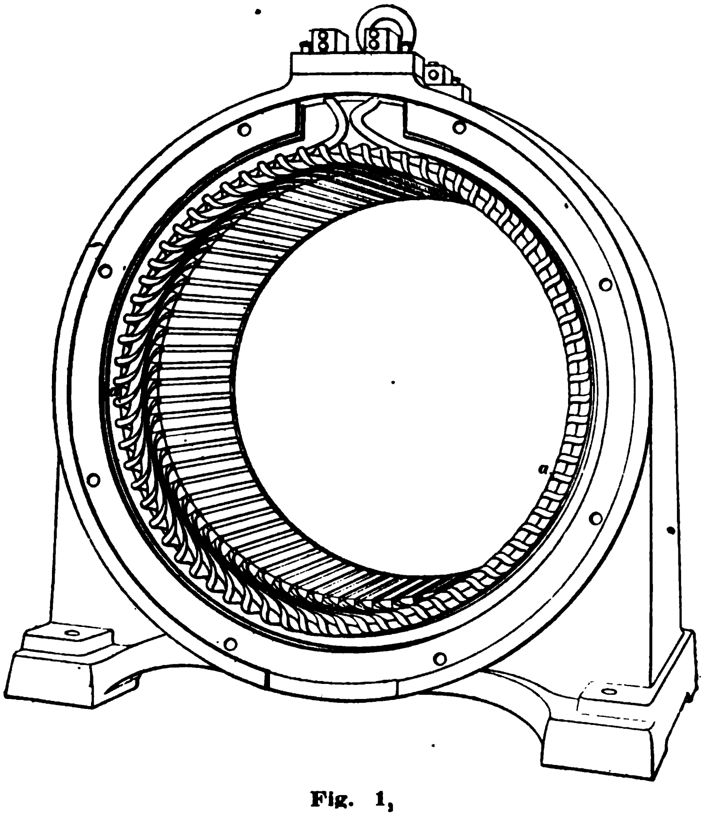

Fig. 1.

(*) Single-phase induction motors are outside the scope of this paper.

The stationary part or *the stator* of the induction motor (Fig. 1), is a laminated iron frame provided with a regular three-phase winding similar to that of a three-phase alternator, this winding being connected to the line. The revolving part or *the rotor* is provided with a winding short-circuited on itself; in our particular motor the winding is of the

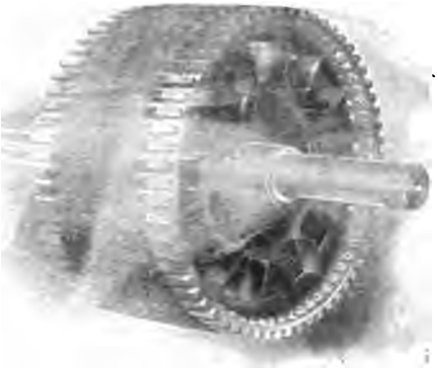

Fig. 2.

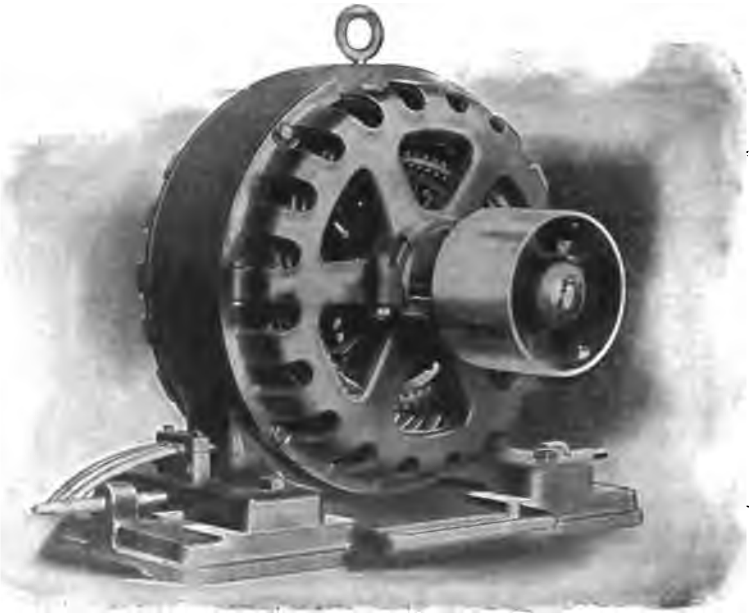

Fig. 8.

so-called "squirrel-cage" type, (Fig. 2), that is to say it consists simply of copper bars slightly insulated from the iron and connected on both ends to metallic rings which complete the circuit among the bars. A general view of the motor is shown in Fig. 3.

The action of the motor is as follows: the currents in the stator produce a revolving magnetic field; the lines of force of this field cut the conductors of the secondary winding and induce in them secondary currents. These currents are of such direction as to be attracted by the revolving field and this attraction causes the armature to revolve. The speed of the revolving field depends on the frequency of the line currents and the number of poles of the stator. During one alternation of the supply current the field travels from one pole to the next pole; therefore the number of revolutions of the rotating field per minute is equal to the number of alternations (frequency) of the system divided by the number of poles of the stator winding. For instance, on ordinary 7200 alts. lighting circuits the revolving field of a 6-pole induction motor makes 7200 ÷ 6 = 1200 revolutions per minute.

The speed of the rotor is lower than that of the revolving field, in order that the lines of force may cut the secondary conductors. In practice, the speed or the armature at full load is a few per cent less than that of the revolving field; for instance, the actual speed of the above-mentioned motor would be somewhere near 1140 r.p.m. This difference in speed is called *the slip* of the induction motor and is usually measured in per cent of the speed of the revolving field, which latter speed is also called the *synchronous speed.* Thus the synchronous speed of the above motor is 1200 r.p.m. and the slip at full load is

$$\frac{1200 - 1140}{1200} = 5\%.$$

The slip depends on the load of the motor and increases with it. At no-load the motor runs almost synchronously, because even a small difference of speed between the revolving field and the rotor is sufficient to induce currents in the latter, furnishing torque necessary for overcoming the friction and windage. As the load increases, the slip increases, the rotor runs more slowly, and the induced currents become larger; in consequence, the torque on the motor is also increased, as it ought to be. When the load exceeds a certain limit, the motor "pulls out" and comes to a stop. The overload capacity of an induction motor

is usually measured by the ratio

$$\frac{\textit{pull-out torque}}{\textit{full-load torque}};$$

This ratio varies from 1.3 to 2.5 and higher according to the size, type and purpose for which the motor is designed.

Induction motors with squirrel-cage secondary cannot be started by simply switching them on to the line (except in very small sizes), because the rush of current during the first moments would be too large.

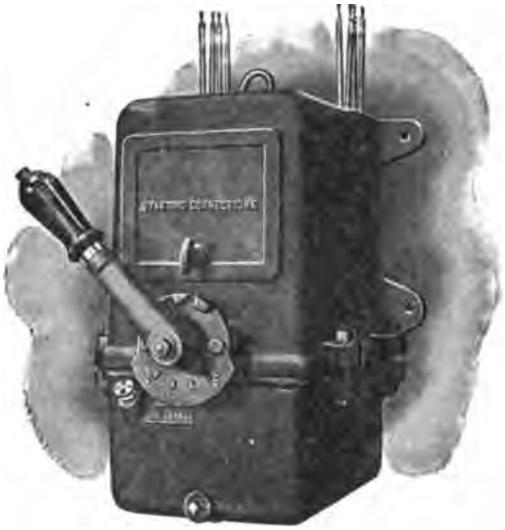

Fig. 4.

The starting is done at a voltage considerably lower than that of the line, and then, as the motor gains in speed, the voltage is increased in a few steps to that of the line. The gradations of the voltage are provided for by means of two auto-transformers (V-connected) and a special controller or switch, usually oil-immersed for safety and durability. The transformers and the switch are enclosed in a common case, and the apparatus is called an "auto-starter" or "compensator" (Figs. 4 and 5).

An induction motor with a squirrel-cage secondary is essentially a constant-speed motor as the difference in speed between no-load and full load is but a few per cent. The starting torque of this type of motors is not very high, the motor being started on a low voltage.(*) For

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(*) According to the general theory of induction motor, the torque decreases as the square of the voltage.

driving machine shops and similar purposes for which shunt-wound direct-current motors are commonly used, a squirrel-cage induction motor

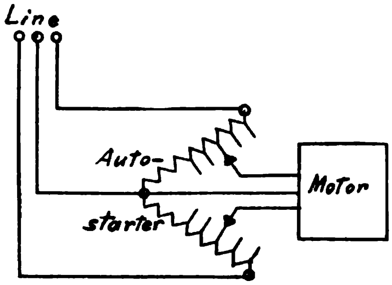

Fig. 5.

is well adapted. There are cases, however, in which a variable-speed duty with high starting torque is required, as for instance in crane, hoisting and similar work, for which direct-current series-wound motors are used as a rule. For such service the rotor of the induction motor is made phase-wound (with the same number of poles as the stator). The ends of the winding are led to three slip rings whence connections are made to a three-phase variable rheostat. At starting, the rheostat is all connected into the circuit and the motor started at the full line voltage with a powerful torque equal to several times full-load torque. Then the rheostat is gradually cut out and if necessary used for speed regulation; the more resistance there is in the circuit, the lower becoming the speed of the motor.

The experiment essentially consists in a brake test on the motor; the *efficiency* is determined as the ratio of the mechanical output measured by the Prony brake, to the electrical input read on the wattmeter. The *power factor* is figured out as the ratio of true watts to apparent watts (volt-amperes). If in addition the speed of the motor is measured, this includes all the necessary data for plotting the performance curves. As it would be hardly practicable to provide separate instruments for each phase, a special "polyphase board" is provided, by means of which the same instruments can be used in succession in the three phases.

The electrical power input is measured by the so-called two-wattmeter method, as shown in Fig. 6. One of the line wires, say *2*, is assumed to be a common return wire for two other wires; the power is measured between the wires *1* and *2* and then between *3* and *2* and the wattmeter readings are added together in order to get the total input into the motor. Accordingly, the series winding of one wattmeter is connected into the line *1* and its shunt winding across *1* and *2*. The series winding of the other wattmeter is connected into the line *3* and the potential winding across *3* and *2*. With the above-mentioned polyphase board only one wattmeter is needed; it is connected in succession in two positions shown in Fig. 6, and the readings added together.

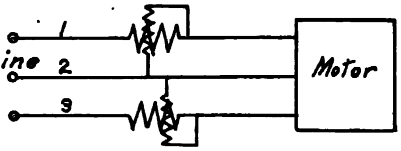

Fig. 6.

Theory and experience show that this method gives correct results for the total power input on unbalanced as well as on balanced loads. However the two component readings are equal only when the load is balanced and non-inductive (power factor of 100%). With an induction motor the load is practically balanced in the three phases, but the power factor is always less than 100%. Accordingly one of the wattmeter readings is always smaller than the other. On light loads, when the power factor becomes less than 50%, one of the wattmeters begins to give negative deflections. Then it is necessary to reverse the potential leads and to take the ***difference*** of the two readings instead of their sum.

For this reason it is advisable to begin the test at the maximum load (say 25% overload), where the power factor is surely higher than 50%, and then reduce the load by steps down to zero. Then one cannot miss the point at which it becomes necessary to reverse the leads of one of the wattmeters.

Measuring the speed and the slip of the induction motor deserves special mention. The speed depends on the load and on the frequency of the supply currents, as the latter determine the speed of the revolving field. Now, if the power for testing the motor is taken from a commer-

cial supply, the frequency may be at times several per cent above or below the normal, and unless the exact frequency is known at the time when the speed is taken, the speed determination is of little value.

To get the speed of the supply, a small *synchronous* motor can be run from the same source and its speed taken simultaneously with that of the induction motor. Another method is to measure simultaneously the speed and the slip of the induction motor; their sum will give the synchronous speed and consequently the frequency of the supplied currents. If, for instance, the speed was 702 r.p.m., and the slip 22 r.p.m.; if the motor is a 10-pole machine, the frequency of the supply was at that particular moment 7240 alterations per minute instead of the standard 7200. In plotting the speed curve the corresponding correction must be made.

Different types of *slip indicators* or instruments for measuring slip of induction motors are in use. One of them that we have in our laboratory is in its principle a commutator with as many parts as the motor has poles—(in our case six). This commutator is pressed against the end of the shaft as an ordinary speed counter and at the same time connected through a resistance to the power supply and to a sensitive ammeter, as shown in Figs. 7 and 8. If the speed of the motor was

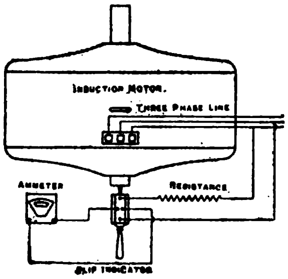

Fig 7.

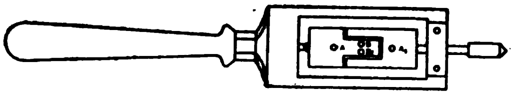

Fig. 8.

exactly synchronous the impulses of the current sent through the commutator into the ammeter would be always at the same point in the alternating e.m.f wave and its indication would be steady. As, however, the motor *lags* behind the revolving field, these impulses occur now at the maximum of the wave, now at the intermediate values, and the needle of the ammeter swings at a speed equal to the *difference* of the speeds of the revolving field and the rotor, or proportional to the slip of the motor. If the slip is not too high, the number of swings per minute can be easily counted and the slip calculated. An alternating-current or polarized bell can be used instead of an ammeter and the number of strokes per minute counted.

Another simple slip indicator also used in our laboratory consists of a flat spring vibrating synchronously under the influence of an electromagnet energized from the A. C. line. This spring is observed through a disk mounted on the shaft of the motor and provided with a radial slot. If the motor could revolve synchronously, the spring would appear to the eye standing still (stroboscopic phenomenon) ; as the motor lags behind the speed of synchronism, the spring appears to be swinging up and down, and from the number of its strokes per minute the slip can be determined.

Speed readings as a rule are not very accurate when an ordinary Prony brake is used, because it is difficult to keep the load constant, say for a minute or so, while the speed is measured. The following method is used when a greater accuracy is required, and no improved brake or transmission dynamometer is at hand. The speed is not measured at all during the brake test, or at least the readings are considered as an approximation only. Then after the test the motor is belted to a dynamo which is loaded on a rheostat, and a curve is taken giving the speed of the motor for different amperes input to the motor; the speed can now be measured with a sufficient accuracy since the rheostat load can be kept fairly constant. From the other test the torque corresponding to the same amperes is determined. By combining these data the speed-torque characteristic can be plotted.

The results of the test can be conveniently plotted in curve form to hp output as abscissae (Fig. 9). Plot *true hp input* (watts ÷ 746), *apparent hp input* (volt-amperes ÷ 746), and *hp output* (for a compari-

son of the above two curves). From these three curves two other curves can be easily plotted: namely, *the efficiency curve*, which represents the ratio of hp output to true input, and *the power-factor curve*, or the ratio of true input to apparent input. In addition to these plot on the same sheet curves of *torque (in ft.-lbs.), speed in rpm.*, and *slip in %* . A set of these curves gives all the necessary information in regard to the performance characteristics of the motor.

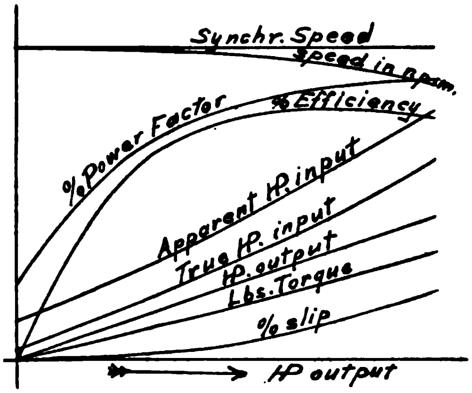

Fig. 9.

It is interesting to check at least one point on the efficiency and power factor curves by calculating separate losses in the motor. The losses consist of I^2R loss in the primary and secondary windings and of no-load losses (iron loss and friction). Theory and experience show that these latter can be assumed as practically constant on all loads and having the same value as at no-load (hence the name "no-load losses"). The primary copper loss can be easily calculated if the primary current and the resistance of the primary winding are known. The secondary copper loss is proportional to the per cent slip, as is shown in the general theory of induction motors.

The details of calculation can be best shown in a numerical example. Suppose that it is desired to check the efficiency and the power factor curves of a 10 hp, 440-volt, three-phase induction motor at full rated load. Let the following data be given at this particular load on the performance curves: slip 4.9%, current input 13.5 amp. per phase. Suppose also that we have from the test data, that the motor consumes 800 watts at no-load and that no-load current is 5.5 amps. The resistance of the primary winding was found to be 0.75 ohm. per phase.

In the first place we figure out the iron loss and friction; these are equal to 800 watts less a correction for the copper losses in the primary and the secondary. But the secondary copper loss is negligeable at no load, because the slip is very small. Thus the correction amounts to $3 \times 5.5^2 \times .75 = 68$ watts, and the losses in question are equal to

$$800 - 68 = 732 \text{ watts.}$$

Now we can determine the losses at 10 hp. output. As was stated above, the secondary copper loss represents a percentage of the input into the secondary equal to per cent slip at this particular load. Thus the input X into the secondary is calculated from the equation

$$\frac{X(100 - 4.9)}{100} = 10 \text{ hp.},$$

whence $X = 10.52$ hp, or 7850 watts. This energy must be supplied from the line, besides 732 watts to cover the iron loss and friction. The primary copper loss amounts to

$$3 \times \overline{13.5}^2 \times .75 = 410 \text{ watts.}$$

so that a total of

$$7850 + 732 + 410 = 8992 \text{ watts}$$

must be supplied to the motor for an output of 10 hp. Thus the efficiency is

$$\frac{7460}{8992} = 83\%,$$

and this must check with that given on the efficiency curve, as obtained from a direct brake test.

The power factor at this load is

$$\frac{8992}{13.5 \times 440 \times \sqrt{3}} = 87.5\%;$$

this should also be the same as given on the power-factor curve.

This method of figuring out efficiency is often used as a check on the wattmeter readings of a brake test. Experience shows that it is more difficult to keep a wattmeter in calibration than a voltmeter or an ammeter. Besides, an error is introduced by the wattmeter readings not being taken simultaneously. In figuring the efficiency from the losses the wattmeter readings are not considered at all; only the ammeter readings and the slip. For no-load losses a special low-reading wattmeter is generally used, and, as in this case there is no brake to make the readings fluctu-

ating, the no-load wattmeter readings are as a rule much more reliable than those taken when the brake is on.

The laboratory experiment should be conducted as follows:

(1) Wire up the motor and let it run light for about 30 minutes to warm up the bearings.(*)

(2) Load up the motor to about 25% above its rated capacity, and keeping the load as steady as possible, read volts, amperes, watts, lbs. brake load, speed and slip.

(3) Reduce the brake load by approximately equal steps to zero, taking at each point the same readings as above.

(4) Check carefully the readings of watts and amperes at no-load.

(5) Measure the resistance of the primary winding by the usual drop of potential method, using of course direct current.

* * *

In your report plot the performance curves to hp output as abscissae. The curve sheet must comprise the following curves: apparent hp input, true hp input, hp output; efficiency and power factor; speed, torque and per cent slip.

Check at least one point on the power factor and efficiency curves from the losses, as was explained above.

Plot on a separate sheet curves of total losses, primary and secondary I^2R losses, and iron loss + friction, against hp output as abscissae, so as to have a clear picture of the relative importance of these losses at various loads.

* * *

In addition to the motor with a squirrel-cage secondary, we have in the laboratory an induction motor with a *phase-wound rotor,* provided with three slip rings, by means of which additional resistance can be introduced into the secondary circuit. There are two cases where such motors can be advantageously used:

(1) On intermittent service where a heavy starting torque is required (cranes, elevators, railway work).

(*) This requirement is quite essential in practice, but can be omitted in the laboratory to save time. At considerable loads some difference in friction should affect the readings but little.

(2) In cities where induction motors are connected to the same supply with incandescent lamps, and where lighting companies object to the use of induction motors, unless the starting current is limited to a certain percentage of the full-load current.

The advantages of a motor with phase-wound secondary are, that it can be made to give a much higher starting torque with a comparatively small current, and that its speed can be varied within wide limits below synchronism, by regulating the amount of resistance in the secondary. Of course it must be understood that this is not an economical method for varying speed, but it is fully permissible with intermittent loads, where efficiency is not of a prime importance.

The only disadvantage of a phase-wound secondary is that it is more expensive than a squirrel-cage rotor. It is also sometimes claimed that a motor in which starting resistances are used in the secondary is not as fool proof, as a motor having a starter in the primary circuit. This objection, however, can be easily eliminated by a suitable construction of the starting device.

It is not necessary that the students should repeat the whole brake test on this motor. When the motor is brought up to speed and the secondary resistance short circuited, the motor behaves exactly the same as a motor with a squirrel-cage secondary. The only experiment required with this motor is a study of the starting torque and of speed control. This experiment can be conducted as follows:

(1) *A comparison of two methods of starting.* Put on a certain load, say by means of a Prony brake, and start the motor, *first,* by switching the motor on the full line voltage, but having a high resistance in the secondary, the resistance being gradually cut out as the motor gains speed; *secondly,* by the usual method, which is to have the secondary short-circuited, and the primary voltage suitably reduced by means of an auto-tarter.(*)

The starting current depends on the amount of resistance inserted into the secondary, and on the starting voltage if an auto-starter is used. Therefore, for a fair comparison, the best starting secondary resistance and the lowest possible starting voltage must first be found. This can be done for instance for the full-load torque. Knowing the rated hp of

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(*) The starting torque of this motor is different in different positions of the secondary relatively to the primary winding. In order to have comparable results the motor must in all cases be started with the secondary in the same position.

the motor and its normal speed the full load torque can be easily calculated and the brake adjusted for this torque. Now a very high resistance must be introduced into the secondary and gradually cut out until the motor starts. This can be assumed to be the right value of the starting resistance for the first step of the starting rheostat. In a similar way try different taps on the transformers of the auto-starter, until a voltage is found at which the motor starts with the same brake load. This can be taken as the right tap for the first notch of the auto-starter.

Having thus found the proper setting of the starting apparatus for both methods of starting, start the motor at a few different values of starting torque using in succession both methods of starting. Try to read the first rush of the current and its subsequent variation as closely as you can, also note the number of seconds that it takes for the motor to attain full speed. Do this with the purpose of forming a judgment about the relative advantages of both methods of starting.

(2) *Speed control.* Bring the motor up to its full speed by gradually short-circuiting the secondary rheostat and put on approximately full load. Now keep the torque (not horse-power) constant, and gradually reduce the speed by again introducing resistance into the secondary. This corresponds to a practical case when a certain weight is lifted by a crane at varying speeds. Read amperes primary and secondary and the corresponding speeds with different values of secondary resistance.

Speed control by varying the primary voltage is never used because decreasing the voltage rapidly reduces the magnetic flux and consequently the torque of the motor. If time permits, try this method, by connecting the starting resistance into the primary instead of the secondary circuit and observing the behavior of the motor. The same can be done by using the several starting positions of the compensator, if it is large enough to carry the current for a considerable time.

In your report on this motor arrange your data in the form of curves or a table showing the comparative behavior of the motor with the two above described methods of starting; show in particular the amount of starting current and the time that it takes to bring the motor up to speed. In regard to speed control, give curves showing the speed of the motor and the current input as a function of the amount of resistance in the secondary circuit.

SINGLE-PHASE ALTERNATOR.

Voltage regulation on inductive and non-inductive loads.

This exercise is an experimental study of the performance of an alternator under actual load conditions. In order to facilitate the experiment, a single-phase machine is selected. Qualitatively the same phenomena are observed in polyphase alternators, while more measuring instruments are required and the measurements are more complicated.

One of the most important problems in the operation and design of alternating-current generators is that of reducing the fluctuations of the voltage with varying load. These fluctuations, due to the voltage drop in the machine, are particularly objectionable on lighting circuits because of the accompanying flickering of the lamps. Therefore certain requirements and guarantees in regard to the maximum fluctuations in voltage are usually introduced into contracts regarding the performance of alternators. These requirements are now usually stated in accordance with the recommendations of the American Institute of Electrical Engineers in the form of a guarantee of a certain *inherent regulation* of the *machine* (See Report of Committee on Standardization, Section on Regulation, Foster's Pocket Book, p. 302).

This is to be understood in the following way: Suppose an alternator is connected to the line, driven at the rated speed, and loaded to its full rated capacity *on non-inductive* load at the rated voltage, say 2200 v. Then let the load be thrown off and the voltage measured again at the same field current and the same speed. Suppose it to be 2330 volts. Then *by definition* the regulation of the machine is

$$\frac{2330 - 2200}{2200} = 5.9\%.$$

The practical meaning of this is as follows: Suppose this alternator to be running in the evening at practically full load on incandescent lighting, current being supplied to the residences through 2200-110 v. house transformers. The lamps are burning at their rated voltage = 110 v. Now as the time advances towards midnight, lamps are gradually turned off, the load on the machine decreases and the voltage rises, unless the field current is at all times properly regulated. When only a few lamps remain burning, the machine is practically running at no-load and the voltage would be about 2330 volts, or

$$2330 \times \frac{110}{2200} = 116.5 \text{ volts}$$

at the lamps; this is too high for 110 v. lamps, and would considerably shorten their life.

Of course there is always a switchboard attendant in the powerhouse who watches the voltage and regulates the field rheostat accordingly; but, as the load fluctuates all the time, it is very difficult to keep the voltage fairly constant, if the machine has a poor inherent regulation.

Voltage drop in the machine is considerably increased when the load is *inductive* (arc lamps, induction motors, etc.); the lower the power factor the worse being the regulation of the machine.

It would lead us too far to give here physical reasons for this. It may merely be suggested that the more the current lags behind the induced e. m. f. of the machine, the greater is the demagnetizing action of the armature upon the field. This is because, at low power factors, the maximum of the current wave in the armature takes place at moments when the armature coils are nearer in opposition to the field coils, so that their demagnetizing action is most effective. Also the vector of the inductive drop is more nearly in phase with the voltage of the machine. (Compare Figs. 4 and 5.)

The better the desired regulation of the machine, the more expensive it is to build. For this reason, a knowledge of the factors affecting regulation becomes of great commercial importance as well as of purely engineering interest.

As was stated above, the regulation or the voltage drop in the machine depends not only on the value of the load but on its character as well. In other words, it depends upon amperes output and power factor. For this reason the regulation of an alternator cannot be represented by

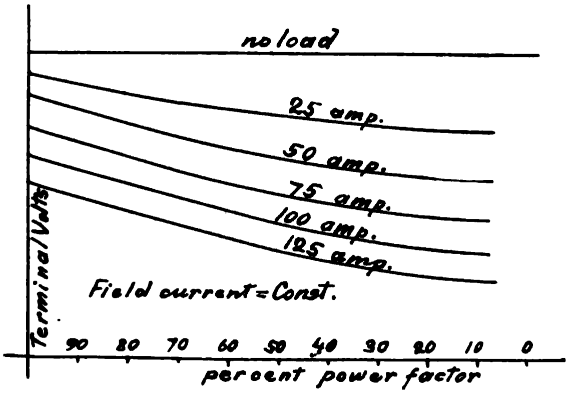

Fig. 1.

one curve, as in case of a direct-current generator, but requires a set of curves, either as shown in Fig. 1 or in Fig. 2. The first set gives the terminal voltage as a function of variable power factor, for constant values of the armature current. The second set of curves gives the values of the same terminal voltage as a function of variable armature current, for constant values of the power factor. The two sets are evidently equivalent and one can be plotted from the other. In taking these curves on an actual machine it is easier to keep the current constant, than to maintain a constant power factor; therefore the results are usually plotted as shown in Fig. 1. Then if desired the ordinates of these curves can be recombined so as to get the curves shown in Fig. 2.

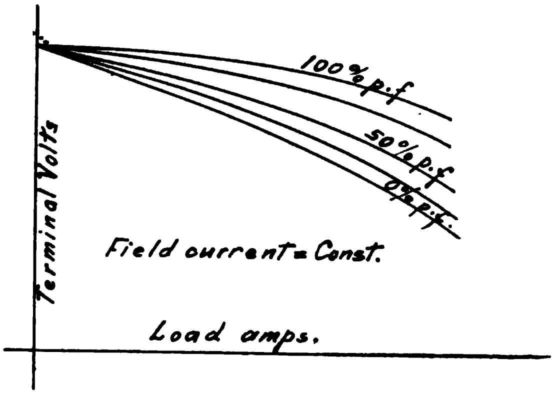

Fig. 2.

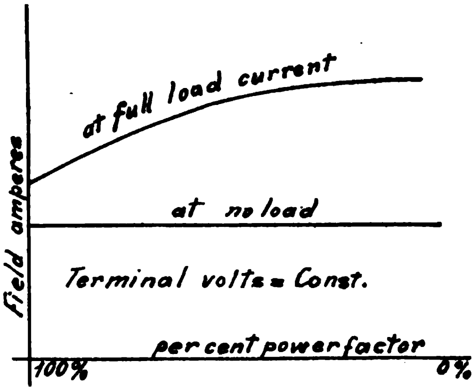

Fig. 3.

With all the above curves the field current is kept constant and preferably at that value which gives the rated voltage of the machine at full load and 100% power factor (see the above given definition of regulation). In actual operation, however, the terminal voltage of the machine rather than the field current is kept constant, and the field excitation is varied according to the load. It is therefore important to know the limits within which the field current must be varied in order to keep the voltage constant (Fig. 3). The designer is interested in this in order to give proper dimensions to the field coils and to the field rheostat. The operating engineer wants to know this curve in order to be able to judge how sensitive the alternator is to changes of load and how difficult it will therefore be to maintain the proper voltage regulation. The curve shown in Fig. 3 may be called the *excitation characteristic* and is taken experimentally in the same way as the curves shown in Fig. 1.

Some analysis of the above experimental results may make clearer the influence of the factors causing the voltage drop in alternators. Generally speaking, total drop is caused by

(1) Ohmic resistance of the armature;
(2) Armature reaction;
(3) Armature self-induction.

The first cause is the same as in direct-current machines. The second one is also present in direct-current machines and consists in armature currents distorting and demagnetizing the original field. The third cause is specifically one present in alternating-current machines only, and is due to the fact that the armature offers not only an ohmic but also an inductive resistance to the passage of the current, this being quite natural since the armature winding is composed of turns wound on an iron frame.

The theory of alternators shows that the armature reaction and the armature self-induction, although they are entirely different phenomena, *have approximately the same influence on the voltage drop in the machine*, so that for practical purposes they can be considered together as an *equivalent* self-induction; this equivalent self-induction is taken large enough to account for the influence of both factors.

From this point of view we can represent the armature of an alternator as possessing a certain ohmic resistance of r ohms and an equivalent inductive resistance of x ohms; the total voltage drop in the arma-

ture can be considered as caused by a combination of these two resistances. Then in accordance with the general theory of alternating currents, we have a vector diagram represented in Fig. 4.

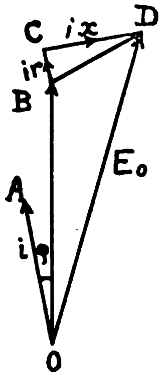

Fig. 4.

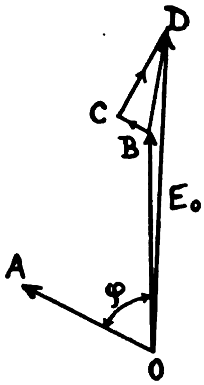

Fig. 5.

OB is the terminal voltage of the machine; *OA* the current, lagging The ohmic drop *ir* in the armature is represented by the vector *BC* parallel behind it by an angle ϕ, corresponding to the power factor of the load. to the vector of the current; the inductive drop *ix* by *CD* perpendicular to the same. *OD* is the induced e. m. f. of the machine and is the geometrical sum of the terminal voltage and the voltage drop in the armature. Beginning with the induced e. m. f., it can be said that the part *DC* is lost in the equivalent inductive resistance of the armature, part *CB* in its ohmic resistance, and the rest, *OB,* is available at the terminals as the line pressure.

Fig. 5 represents a similar diagram for the same values of the exciting and armature currents, but *for a lower power factor* (angle ϕ is larger). It will be readily seen that for obvious geometrical reasons the terminal voltage *OB* is lower in this case than in Fig. 4. This is another explanation of the previously stated fact that the terminal voltage of the machine under similar conditions is lower, the lower the power factor.

Referring now to any of the curves in Figs. 1 and 2, the equivalent inductive resistance *x* of the armature can be figured out for any point on these curves by means of the diagram Fig. 4. The induced voltage (no-load voltage), the terminal voltage, the current and the power factor

are known; the ohmic resistance of the armature can also be easily measured. The only unknown quantity is the inductive drop, ix, which can readily be determined graphically, and the equivalent self-induction x of the armature calculated.

Now, if x were constant as is the ohmic resistance r, it would not be necessary to take *experimentally* all the above curves of voltage drop, they could be easily predetermined from diagrams similar to that of Fig. 4. Unfortunately, x varies appreciably with the exciting current, because it influences the permeability of the iron; it also depends on the value of the armature current, because the same has a bearing on the saturation of the armature teeth, and probably it also depends somewhat on the power factor.

At any rate, experience shows that the terminal voltage cannot be predicted with a close accuracy from the results of a test at a particular load and power factor, these rules being applied for a different load and power factor. At least it does not hold good for all machines and at all loads.

It is desired that the students determine x for different values of the current from the curve shown in Fig. 2, corresponding to the lowest power factor. Then by using these values, or an average as the case may be, a few points on the upper curve in Fig. 2 should be predetermined by using the diagram Fig. 4. A comparison of these points with the points on the curve taken experimentally will show in how far this method is applicable to the machine under test. This comparison may also suggest certain corrections to be brought into the method in order to make it more reliable.

The question of predetermining alternator regulation is one of a vital importance, since it is almost impossible to get a satisfactory artificial load for large modern alternators of several thousand kilowatt capacity and voltages ranging into the ten thousands. There have been several methods proposed by means of which, from a few simple factory tests requiring no artificial load, the regulation of the machine can be *predetermined* theoretically for any desired load and power factor. Unfortunately all these methods are either unreliable, or too complicated for common use, and the whole question is still open for discussion and improvements. A comparatively simple rule was provisionally

recommended a few years ago by the American Institute of Electrical Engineers (See rule 71 of the Report of the Committee on Standardization, Foster's Pocket Book, p, 304). It can now be said, however, with a great degree of confidence that this rule gives wrong results and, what is particularly objectionable, it indicates a better regulation than the machine actually possesses.

The above analysis by means of the diagram Fig. 4 is merely an introduction to this interesting and complicated subject. The question will be taken up more in detail in one of the second term exercises. Even if the question has not yet been solved in its entirety, it is desired that the student should know at least the elements entering into the problem, and the underlying difficulties. This will enable him to understand the current literature on the subject, and will pave the way for his original research along these lines.

NOTE. For a somewhat advanced treatment of the subject of regulation of alternators see the writer's article in the Electric Club Journal, 1904, pp. 532-41.

The connections for loading the machine are shown in Fig. 6.

(1) Begin the experiment by loading the machine so that it gives a full rated non-inductive current at normal voltage; note the corresponding field current. Now this field current and the speed of the machine must be kept constant, while the curves shown in Fig. 1 are taken. The load shown in Fig. 6 consists of non-inductive and inductive resistances connected in parallel, and by regulating these resistances the current and the power factor can be varied within wide limits.

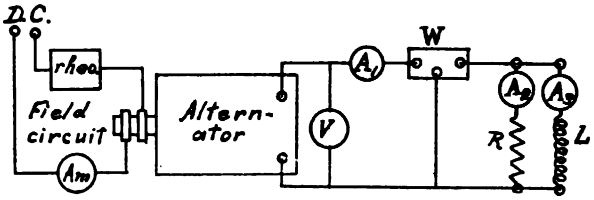

Fig. 6.

Begin as usually with most unfavorable conditions:—lowest power factor and heaviest current (about 25% overload). Keep the current constant and gradually raise the power factor to 100% by cutting out the inductive component of the current and increasing the current

in the non-inductive resistance. This will give the lowest curve in Fig. I. Take all the other curves in a similar manner, and finally throw off the load altogether and measure the no-load voltage (the upper horizontal line).

For each point in the above curves read volts, amperes and watts. It is also interesting to read separately the amperes in the inductive and the non-inductive branches of the circuit (ammeters A_2 and A_3). It will be seen that the arithmetical sum of these currents is always larger than the total current shown on the ammeter A_1, since the two currents A_2 and A_3 *are not in phase with each other;* A_1 represents their geometrical sum (See Fig. 7). In reality all three currents are read on the same ammeter which is connected in succession into the three parts of the circuit, by means of a suitable multi-throw switch (or polyphase board).

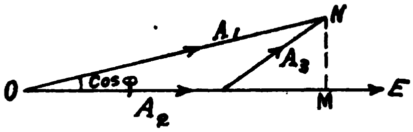

Fig. 7.

(2) Now put on the load again and take the curve shown in Fig. 3. Begin with 25% overload current and the lowest power factor available; vary the field current until the machine gives its rated voltage. Now gradually increase the power factor to 100% keeping the current constant and, at the same time, varying the exciting current so as to keep the voltage constant. Then throw off the load and reduce the field current so as to get the same voltage again. This will give the ordinate of the horizontal line shown in Fig. 3. For each setting of the load read field amperes and watts; keep volts, armature amperes and the speed as nearly constant as possible.

(3) Measure the ohmic resistance of the armature by the usual drop of potential method.

(4) Measure iron loss and friction of the machine so as to be able to figure out its efficiency. For this purpose excite the machine to the same value as in experiment (1), and run it on open circuit, noting the input into the driving motor. Then take off the belt and run the driving motor alone; the input will be smaller, and the difference represents the iron loss and friction of the alternator under test.

In your report give the following results:

(1) Plot the curves shown in Fig. 1, and supplement them by a curve showing *per cent* regulation at full-load current, with different values of power factor.

(2) Explain in an example taken from your data how to convert the above curves into curves similar to those shown in Fig. 2.

(3) Plot the curves shown in Fig. 3, and, assuming the value of the exciting current at full non-inductive load as 100%, show per cent increase of this current as the load becomes inductive. Figure out by what percentage from 100% the field current must be reduced when the load is thrown off, in order that the same voltage be maintained.

(4) Figure out the inductive resistance x of the armature by using the vector diagram shown in Fig. 4 and points of the curve as in Fig. 2, corresponding to the lowest value of the power factor. Plot the values of x to currents as abscissae.

(5) Using the above values of x, predetermine the voltage drop at a comparatively high value of power factor, and compare the results to those observed experimentally.

(6) Figure out the efficiency of the machine at full rated non-inductive load. The efficiency is the ratio of

$$\frac{\textit{output}}{\textit{input}},$$

or, which is the same

$$\frac{\textit{output}}{\textit{output} + \textit{losses}}.$$

The losses consist of no-load losses (iron loss and friction) which were determined experimentally, and of copper losses in the armature and the field winding. Armature I^2R loss is figured out from the rated current and the ohmic resistance measured during the experiment. The loss in the field circuit is the product of D. C. supply voltage times the field current. The output at 100% power factor load is equal to the full rated current times normal voltage of the machine. From these data the efficiency can be easily calculated.

(7) If you are interested in A. C. diagrams, take a set of readings of total and component amperes and construct a triangle as shown in Fig. 7. From this triangle the power factor can be determined without

the use of any wattmeter. See if the value of the power factor determined as the ratio of OM to ON checks with that figured from the wattmeter reading.

NOTE. In figuring out the efficiency of an alternator the excitation loss is usually calculated from the formula i^2r, where i is the exciting current and r the resistance of the field winding. This is not quite correct, since the loss in the field rheostat must also be charged to the machine, because it is an unavoidable loss of energy and is present in every alternator. It is more correct therefore to figure out this loss by the formula ei, where e is the standard voltage of D. C. supply.

When the field current is supplied by an exciter driven by a separate prime mover, it would not be correct to represent the field loss even by the formula ei. It is better to calculate the efficiency of the alternator *without* taking the field loss into account (this however should be plainly stated); then add to the steam consumption of the main engine, the quantity of steam necessary for running the auxiliary engine driving the exciter. Only in this way can the additional expense for excitation be properly accounted for.

See also in regard to this question rules 5 (second paragraph) and 12*f* of the above mentioned Report of the Committee on Standardization.

OPERATING GENERATORS IN PARALLEL.

When electrical machinery is used for generating power it is frequently necessary to have more than one machine installed to supply current to the same line. This is because it would not be economical to run during the hours of small demand for power a machine of capacity sufficient to carry the heaviest load of the day. It is customary to run during such hours of light load say one small machine, and then gradually add to it more machines as the demand for power increases.

In other cases it becomes necessary to have several machines for the simple reason that the total output of the station is larger than the largest generator built at present can supply. There are power houses in operation with outputs of over 100,000 kw, while the largest generating unit built at present is somewhere near 10,000 kw.

With the system of distribution of electrical energy used at present (constant potential system) machines which operate simultaneously are connected *in parallel,* so that each runs at full voltage and supplies a part of the current demand.(*)

There are certain conditions necessary to be fulfilled in order that two or more machines could supply power to the same bus bars without interfering with each other, and each take a proportionate share of the total load.

The conditions existing when generators are operated in parallel can in a most general way be expressed thus:—when but one generator is connected to the line, the power generated can flow only into the line; when, however, another machine is connected to the same line, the current from the first machine, instead of flowing to the line, may under certain circumstances also flow into this second machine, driving it as a motor. In this case the second machine not only does not help the first one, but merely constitutes an additional useless load for it. Even if this is prevented and both machines are working as generators sending power into the line, it does not necessarily follow that each machine takes its proper

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* With distribution at a constant current, for example, for arc lighting, or as is proposed for certain long-distance transmission lines, the machines, if more than one are used, must be connected *in series*, each supplying the total line current, and taking a part of the total voltage. The considerations of the present article do not apply to such systems.

share of the total load, and that, when the load fluctuates, the current is still divided in the right proportion between the machines.

The purpose of this exercise is to study experimentally the conditions which exist when two machines are working in parallel; also to observe the difficulties encountered in such operation and to note some remedies. Direct-current generators and A. C. machines are considered separately.

1. Parallel operation of direct-current machines.

Of the two usual types of direct-current machines—shunt-wound generators and compound-wound generators—the former are more easily operated in parallel and shall therefore be discussed first.

(a) *Shunt-wound generators.* If two machines are identical or at least have similar electrical characteristics and are driven by identical prime movers they usually run satisfactorily in parallel and automatically divide the load in two equal parts, for there is no reason why one machine should carry more load than the other. *A* and *B* (Fig. 1) are

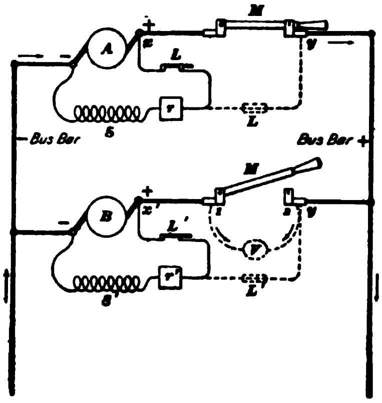

Fig. 1.

the armatures of two generators; *S* and *S'* their shunt-field windings; *r* and *r'* field rheostats; *L* and *L'* field switches. *M* and *M'* are main switches connecting each machine to the station bus bars. In order to simplify the connections the machines are shown in sketch permanently connected to the negative bus bar. Good modern practice, however, requires the use of double-pole switches so that the machine when not running may be disconnected from the bus bars on both sides. Instead

of connecting the field across the brushes of the machine it can be connected direct to bus bars as shown by dotted lines; there is not much difference between the two schemes and both are used in practice.

Thus, suppose that one of the machines is supplying the load and that it becomes necessary to put the other machine in operation. The machine is first excited so as to give the same voltage as the first, and the right polarity of course; then the main switch of the second machine is closed. The first machine will still continue to supply the total load unless the excitation of the second machine be somewhat *increased* and that of the first machine *reduced*. By regulating the field rheostats of both machines, the load can be divided in any desired proportion, and if the machines are identical each will take the desired share of load even with fluctuating current and voltage.

If it is now desired to disconnect one of the machines and to transfer the whole load to the other machine, this should *not* be done by simply opening the main switch of the first machine. This would cause an arc at the switch, the line voltage would drop, and the second machine would experience a harmful shock as the extra load is suddenly thrown upon it. This may not be noticeable on small laboratory dynamos, but is of consequence in case of large machines.

Therefore, before opening the main switch of one of the machines its field excitation must be *lowered* and that of the other machine *increased,* until this latter carries practically the whole load. Then the main switch can be opened without disturbing the established electrical relations. By lowering the field excitation of the first generator still more, the armature current is reversed, and the machine begins to run as *a shunt motor,* driving its prime mover. This of course must be avoided in practice, but should it accidentally occur, no particular harm would be done as the machine would continue to run in the same direction. Some power houses are provided with "reverse current relays" or special circuit breakers which open the circuit of the machine in case the current should become reversed.

If the two machines have different characteristics, that is to say, if the voltage drop in one differs from that in the other with increasing load, it may easily follow that while the machines divide the current properly at a certain load, that machine which has the smaller internal drop will become relatively overloaded on heavier loads, and *vice versa.* Under such circumstances it becomes necessary to artificially "spoil" the

characteristics of the better machine, by connecting some resistance in its armature circuit until it gives the same per cent drop as the other machine; then the machines will work satisfactorily under all load conditions. Should a difficulty of this kind present itself in the laboratory, the students are expected to apply this remedy.

(b) *Compound-wound generators.* Two compound-wound machines in parallel are shown in Fig. 2. The general scheme of connections is the same as in Fig. 1, except for the addition of the series windings of the machines; the series windings are provided if necessary with German silver regulating shunts.(*) It may seem as first that the addition of series windings should in no way affect a satisfactory operation of the machines, and that all that was said above in regard to shunt-wound machines is directly applicable to compound-wound generators.

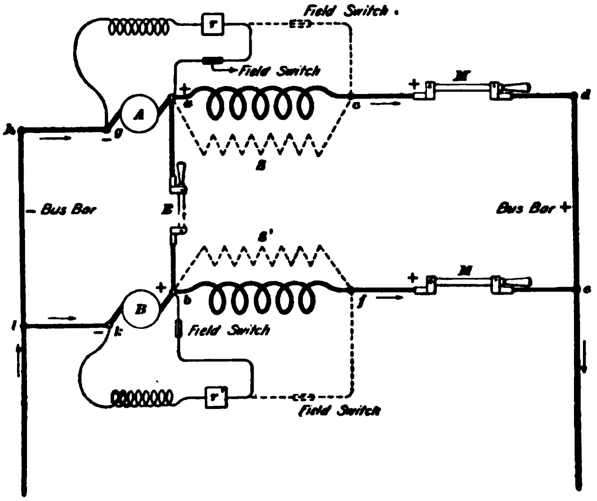

Fig. 2.

Experience shows, however, that *two compound-wound generators do not run stable enough in parallel, unless an equalizing connection E is established between the points a and b, as shown in Fig. 2.*

The cause for this is as follows: Suppose first that the switch *E* is open so that there is no equalizing connection, and assume that for

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* For general properties and applications of compound-wound machines, as well as in regard to the use of the German silver shunt, see the Note entitled "direct-current generator Characteristics." p. 113.

some reason one of the machines, for instance *B*, gives a slightly higher induced e. m. f. The result would be that this machine would take a slightly larger share of the load than *A*; therefore a larger current will flow through the compounding winding of *B* than through that of *A*. The consequence will be that the e. m. f. of *B* will be *still more increased*, and the share of load of machine *A* again decreased. This will continue until *B* will carry all the load and *A* will run at no load; after this, unless the machines are provided with reverse-current circuit-breakers, *B* will reverse the current in *A* and will drive it as a motor. Such an incident would do no harm to a shunt machine, as was mentioned above, but with a compound-wound machine the reversed current flowing through the series field weakens the original shunt field and the machine begins to run faster and faster, driving its prime mover. By this time the other machine becomes overloaded and slows down. Now the machine *A* having a higher e. m. f. because of a higher speed, will cause a sudden rush of current into the line and into the machine *B*; the phenomenon repeats itself with the machines exchanging their relation of driver and driven.

Whether or not this explanation is exactly correct experience shows that two compound-wound generators do not work satisfactorily without an equalizer between the points *a* and *b*; the load is distributed unevenly between the machines from moment to moment and the current is easily reversed.

The action of the equalizer is as follows: Suppose, as before, that for some reason the induced e. m. f. of the machine *B* is higher and therefore the current supplied by it larger than that of the machine *A*. This causes the ohmic drop between *b* and *e* to be larger than that between *a* and *d*; but with an equalizing cable between *b* and *a*, of a negligible resistance, this is impossible, and thus part of the current of the machine *B* instead of flowing from *b* to the positive bus-bar directly through *e*, flows to the same bus-bar through the equalizer *E* and the series winding of the machine *A*. This results in the field of the machine *B* being strengthened *less* than it would be without the equalizer, while the field of the weaker machine *A* is strengthened by the excess of the current of the other machine; the machine *A* is thus helped to keep up its voltage. In short, *the equalizing connection prevents the currents in the series fields of two or more machines from differing widely from each other, however different their armature currents might be.* Therefore,

when connected by an equalizing bus, different machines cannot have widely different voltages; cannot easily have the load disproportionately distributed and the more remote becomes the possibility for one machine to pump power back into the other machine, driving it as a motor.

In Fig. 2, as in Fig. 1, for simplicity of explanation the machines are shown permanently connected to the negative bus-bar. In practice it is much better to have a switch between *h* and *g* and between *l* and *k* in order to be able to disconnect either machine entirely from the line. With such switches the operation of putting two compound-wound generators in parallel is as follows:

Suppose the machine *A* to be running and supplying the load, and suppose it to be required to put *B* in parallel with it. All the switches of the machine *B* as well as the equalizing switch *E* are open. First the shunt field switch of the machine *B* must be closed and the machine excited so as to give its full voltage; then the switches *E* and *M'* must be closed in order to have part of the current of the machine *A* flowing through the series field of the machine *B*. Then after the voltage of the machine *B* is properly adjusted to that of the bus-bars, the last switch between *k* and *l* can be closed and the excitation brought up so as to properly distribute the load between the machines. In disconnecting one of the machines the switches must be opened in reverse order.(*)

Two or more *identical* compound-wound machines, provided with suitable equalizer connections, as explained above, naturally distribute the current among themselves equally well at all loads. A difficulty arises, however, when the machines have *different characteristics,* as was explained in the case of shunt-wound generators. The conditions under which two compound-wound machines of different types can be satisfactorily operated in parallel are as follows

In the first place both machines must have the same degree of compounding or over-compounding when running separately; if this is not the case the machine which has a higher degree of compounding will take a larger share of the total output, as the load increases, because

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(*) With large machines it is desirable to have three separate switches as described above. With medium size machines two switches connecting the machine to the bus bars can be united into one double-pole switch, though in this case the machines cannot be thrown in parallel as smoothly, because the main circuit becomes closed before the field is properly adjusted. In inexpensive isolated plants three-pole switches are sometimes used, combining all the three switches in one; with small machines the momentary rush of current is not considered harmful.

its induced e. m. f. will be higher than that of the other machine. The equalizing connection cannot remedy this fault. Another condition to be fulfilled is that when each machine is delivering its proper share of the load, the drop between *a* and *d* must be equal to the drop between *b* and *e*; otherwise an equalizing current will flow through *ab*, which is wrong when the machines are delivering each the right current. As a general case, the resistances *ad* and *be* do not satisfy this requirement, and it becomes necessary to introduce some artificial resistance into one of them. Then the machines divide the current properly under all conditions of load.

The students are given in the laboratory two shunt-wound machines of different type possessing different characteristics; the experiment should be conducted as follows: The machines should be connected in parallel as shown in Fig. 1 and loaded on a rheostat. Take a moderate load and practice transferring it from one machine to the other, by regulating the field rheostats. Also start and stop one of the machines when the other is running, without disturbing the load. Weaken the field of one of the machines until the current in it reverses and it is driven by the other machine as a motor. Try to run one or both machines in parallel with the laboratory D. C. supply.

After this investigate whether the machines divide the load properly at all loads. Take a load nearly equal to the total capacity of the two machines and adjust the field rheostat so that each machine takes its share of the load. Now gradually decrease the load and observe if the load is all the time divided in about the same proportion. If not, introduce some resistance into the armature circuit of the machine that has a tendency to take a larger amount of the load; adjust the resistance to the best value, and then take a complete curve from full load to no load, showing the current distribution between the two machines.

Now provide the machines with a series winding, and investigate their performance in parallel, as compound-wound generators. As was stated above, three conditions are necessary in order that the machines shall operate satisfactorily:

(1) An equalizing connection must be provided.

(2) Both machines must have the same degree of compounding or over-compounding when running alone.

(3) Drop in *ad* must be equal to that in *be* (Fig. 2).

First try to run the machines without having any of these conditions fulfilled, and see what occurs as the load is varied. Then gradually introduce the above modifications and observe the improvement in operation. Try to obtain a satisfactory operation at all loads and take a curve showing the division of the load between the two machines.

The performance is considerably influenced by the resistance of the equalizer wire. The lower this resistance the better is the equalization of exciting currents and therefore the more satisfactory the operation of the machines. Take a few readings with the same load but with different resistances in the equalizing circuit, so as to observe the influence of this factor.

In your report give the following data and information:

(1) Report concerning your preliminary experiment with two shunt-wound machines and give some numerical data to illustrate the observed phenomena.

(2) Plot to total load as abscissae: current delivered by each machine and the voltage at the bus bars; these data should refer to the operation of the machines after some resistance has been introduced into the circuit of one of them.

(3) Describe illustrating by numerical data, what difficulties you experienced in operating the two compound-wound generators without having the above mentioned three conditions fulfilled.

(4) Give similar curves for compound-wound machines as in the requirement (2); show also the current in the equalizing connection.

(5) Describe your findings in regard to the influence of the ohmic resistance of the equalizing connection.

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2. *Parallel operation of alternators.*

Two direct-current machines can be put in parallel as soon as their voltages are approximately equal; while in putting two alternators in parallel three conditions must be fulfilled; namely,—the machines

(1) Must give the same voltage;

(2) Must have the same frequency;

(3) Must be *in phase* with one another.

Unless all these requirements are fulfilled, one of the machines would send part of the current into the other machine, instead of sending it to the line. Only when the e. m. f.'s of both alternators are equal *at all*

moments—which means the fulfillment of the above three conditions—their actions are properly combined and each sending its current to the line.

Let us investigate somewhat more in detail what would occur if two alternators be connected to the same bus bars without all of the previously-stated conditions being fulfilled.

(*1*) If the two machines are excited so as to give *different voltages,* the other two conditions being fulfilled, a wattless current would circulate between the two machines, leading for the machine excited lower and lagging with regard to the machine excited higher. The action of this current will consist in strengthening the field of the first machine and weakening the field of the second machine; the resultant voltage at the bus bars will be somewhere between the voltages of the two machines. The set may still work satisfactorily, provided this wattless current is not too heavy, but it does not help the operation and gives an unnecessary I^2R loss in the armature of both machines. If this wattless current is sufficiently large, it may heat up the machines or blow out the fuses, though the external load may be quite small.

(*2*) If the machines have *not the same frequency,* the current that they would supply would be an interference current without any definite frequency, and could not be used either for lamps or motors. To see this clearly, draw two sine waves of frequencies differing say 5% one from the other, and add them together. Moreover, under such circumstances each machine would be short-circuiited on the other; in fact, if coupling without synchronizing is attempted, the circuit-protecting devices immediately open the circuit.

(*3*) If the machines are *not in phase* (the maximums of their e. m. f. waves not occurring at the same moments), a current circulates between the two machines, under a pressure equal to the difference of their e. m. f.'s, and we have again the conditions described above under (*1*). It may also be pointed out here, that if the two machines have *different wave forms,* equalizing currents are always present to some extent, but unless the wave forms are very much different, these currents do not do much harm except to cause additional heating of the machines, and to lower somewhat their efficiency.

The process of bringing an alternator to the voltage, frequency and phase of another alternator is called *synchronizing* (the word literally means "bringing in the same time"). Knowing the frequency of the

supply and the number of poles of the machine to be synchronized, it is an easy matter to determine the speed necessary in order that it may give the same frequency. If for instance the machine has 30 poles, it gives 30 alternations during one complete revolution; so that if the frequency of the supply is 7200 alterations per minute, the machine must revolve 7200 ÷ 30 = 240 times per min. in order to give this number of alterations. The simple rule is: the speed of an alternator in r.p.m. must be equal to the frequency of the supply (in alts. per min.) divided by the number of poles of the machine.

After this speed has been approximately obtained, the field of the alternator is so adjusted as to give about the same voltage as that of the bus bars to which the machine is connected. Now it only remains to bring the machine *in phase* with the voltage at the bus bars. This is done by means of properly connected incandescent lamps (synchronizing lamps), or special instruments, so-called synchroscopes or synchronism indicators.

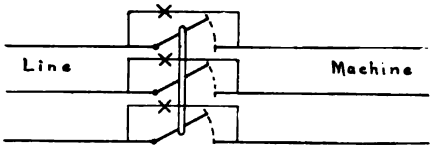

Fig. 3.

Synchronizing lamps are connected, as shown in Fig. 3, around the main switch that connects the machine to the bus bars. So long as the alternator is not in phase with the line, equalizing currents circulate through it, and the lamps serve both to reduce and to indicate these currents. By varying the speed of the alternator, it is possible to extinguish the lamps; this will show that the machine is in perfect synchronism, and the switch can be closed.

You are warned against closing the switch too soon; the lamps should remain extinguished several seconds at a time, in order to be sure that the machine is sufficiently near synchronism.

Students may first try to synchronize one phase, using the alternator as a single-phase machine. After this has been successfully accomplished, the synchronizing of three phases may be tried.

If two 220 v. single-phase machines are to be put in parallel, at least four ordinary 110 v. synchronizing lamps should be used in series,

because during synchronizing at certain moments the e. m. f.'s of the machines may be acting in the same direction instead of in opposition, thus giving 440 volts. It is even better to have under these conditions 5 lamps in series, so as not to let them glow too brightly; then it is easier to observe the periods of the extinguishing of the light.(*) Some prefer to connect the lamps as shown in Fig. 4; in this case the machines are in synchronism when the lamps glow brightest. The student should try this arrangement too, though it is generally acknowledged that it is easier to observe the moments of complete extinguishing of the light, than the brightest moments.

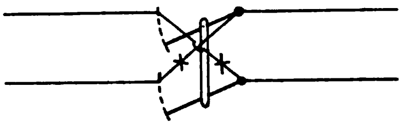

Fig. 4.

As an advantage of this latter arrangement it is claimed that should a lamp burn out during the process of synchronizing, the operator would immediately notice this, while with the first arrangement he may judge by the lamp being extinguished that the machines are in perfect synchronism. Thus he might close the switch of the machine while it was altogether out of phase, and unless the protective devices (fuses or circuit-breakers) operate promptly the machine may be damaged by the rush of current. The possibility of a synchronizing lamp burning out is, however, quite remote, and with two or three-phase machines the burning out of one set of lamps would not affect the others.

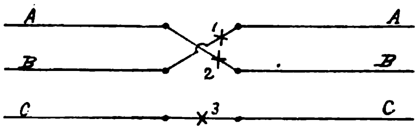

Fig. 5.

The crossing of lamps with three-phase machines (Fig. 5) is very convenient, especially if the lamps are arranged in a circle (Fig. 6). In

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* For synchronizing high-tension alternators, lamps are connected through small transformers, so-called voltmeter or shunt transformers.

this case, maximum brightness occurs in the three sets of the lamps in rotation, so that the light appears traveling along the circle. The direction in which the light rotates depends on whether the speed of the machine is too low or too high. When the machine is in synchronism, lamps marked "3" are dark, while lamps "2" and "1" glow brightly.

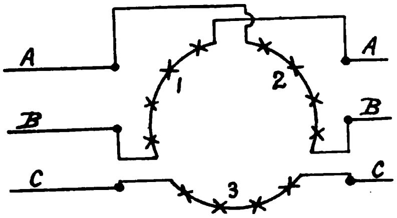

Fig. 6.

In large power houses, where the engines are placed far from the switchboard, it is convenient for the man at the throttle to see directly whether his machine is running slow or fast, without any signals from the switchboard attendant. With the above arrangement of lamps he can see the light traveling in one direction or the other and regulate the speed of the engine accordingly. This saves time in synchronizing large machines.

Sometimes steam engines are provided with small electric motors operating their governors, so that the speed of the engine can be regulated from the switchboard.

Ordinary A. C. voltmeters can be used for synchronizing instead of lamps; a voltmeter can be safely connected between the machines because of its high resistance. When the machines are in synchronism, the voltmeter pointer comes to zero, while otherwise it swings all the time and makes it difficult to catch the right moment.

During the last few years, synchronizing lamps and voltmeters have given place to special synchronizing instruments, so-called synchroscopes or synchronism indicators. These devices have the appearance of ordinary switchboard instruments, except that there is no retaining spring or weight, and the pointer is free to revolve through 360°. When the speed is too low, the pointer revolves in one direction; if it is too high, it rotates in the opposite direction. When the speed is right, the pointer stands still, and when the machine is in phase it shows zero, indicating that the switch can be closed.

The construction of the synchronism indicator which we have in our laboratory is similar to that of a small split-phase motor; the field of the motor is energized from the machine that is already supplying power to the line, and the armature is connected to the machine to be "thrown in". Figs. 7 and 8 show the scheme of connections of this device.

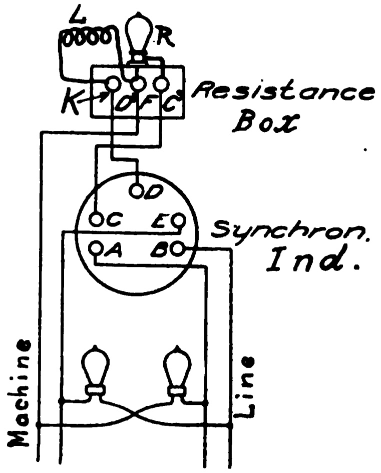

Fig. 7.

The armature of the synchronism indicator is of the drum type; it has two coils rigidly fastened at right angles to each other and connected in series. Their junction is connected through a collector ring to the binding post marked *E*. The other two terminals are brought out, also through collector rings, to binding posts *C* and *D*.

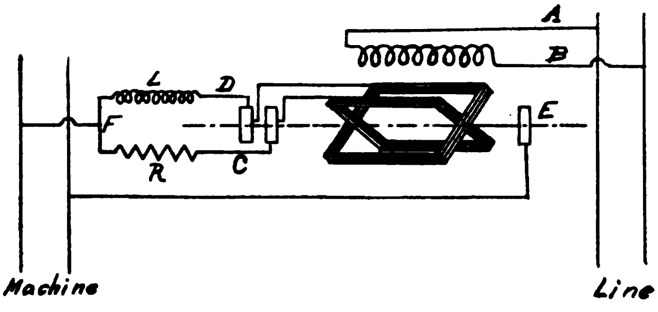

Fig. 8.

A split-phase box K is used with this instrument. It has an ohmic resistance (incandescent lamp R) connected between the terminals C' and F, and an inductance L between D' and F. The purpose of the box can be better seen in Fig. 8. The two armature windings are connected in parallel across the machine terminals; one winding has inductance L in series with it, the other has ohmic resistance R.

This causes currents in the two armature coils to be displaced in phase relative to each other; as the coils themselves are also displaced geometrically, the two currents produce a revolving magnetic field.

A and B are the terminals of the stationary field winding of the synchroscope; this field is excited from the load bus bars.

Thus we have in this device a stationary pulsating field produced by one machine and a revolving field (split-phase arrangement) produced by the other machine. If the frequencies of both machines are equal, there is a certain stable position of the armature of the synchronism indicator, in which position the interaction between the two fields is practically zero. If, however, the frequencies are different, one sine wave continually changes its phase relation with respect to the other. The position of stability of the armature also continually changes, and the armature revolves at a speed equal to the difference of the frequencies.

Synchronizing is much more easily done with this apparatus than with lamps. In large stations synchroscopes are used having diameters up to three feet, so as to be visible from all points of the room.

Automatic synchronizing devices have recently been put on the market; they operate on the relay principle and automatically close the main switch when the machine is in synchronism. It is not yet possible at this writing to pass judgment regarding the practicability of these automatic synchronizers, but should they prove to be a success they will materially reduce the amount of time necessary for synchronizing large alternators.

After sufficient exercise in synchronizing, it is advisable to spend some time in observing the *energy relations* in the machine working in synchronism with the line. An alternator can work either as a generator supplying electrical power, or as a motor supplying mechanical power; in this latter case it is called a *synchronous motor.* If the alternator is driven by a shunt-wound direct-current motor (as is the case in our laboratory), this transition from generator to motor can be easily

observed. After the machine has been synchronized and connected to A. C. supply, open the main switch of the driving-motor; the set will continue to rotate, the A. C. generator having evidently become a motor, driving the other machine. To make this still more evident, after again synchronizing, instead of opening the switch leave the direct-current motor connected to its supply, and gradually increase its field current. The counter e. m. f. of the motor will also increase, and the current drawn from the line will diminish; when this counter e. m. f. will become higher than the e. m. f. of the supply, the motor will send current back into the circuit, thus becoming a D. C. generator. At the same time the power generated by the alternator will diminish and finally the wattmeter will begin to read in the opposite direction, showing that the machine now takes in power instead of generating it, in other words is running as a motor.

Thus by properly regulating the energy relations in the driving motor the alternator can be made to operate either as a generator or as a motor.

In describing the parallel working of direct-current generators it was explained that the amount of power delivered by one of the machines can be increased by increasing its field excitation. This is not the case with alternators. Increasing the excitation will merely produce *wattless* currents, which tend to produce a demagnetizing action on the field and thus reduce its strength to its former value. The only way of increasing the output of an alternator, working in parallel with other machines, is to increase the input into the driving motor or the prime mover. Then the *working* component of the current will also be increased.

Varying the excitation of the alternator without increasing the input into the driving motor can be tried in the laboratory; it will be seen that though the current can be increased several times, the wattmeter reading will be comparatively little affected, showing that the increase in current was due to a wattless component. Some increase in the wattmeter reading will be, however, noticeable, due to a larger copper loss with heavier currents.

The laboratory experiment in synchronizing alternators should be conducted about as follows:

(1) Practice in synchronizing one phase of the machine, or three phases connected as in Fig. 3.

(2) Synchronize with lamps connected as per Fig. 5.

(3) Try synchronizing with a voltmeter.

Repeat each experiment several times, and give your opinion as to how long it should take to synchronize the set under ordinary commercial conditions, from the time it is started from rest, until it is connected to the bus bars and takes its share of load.

(5) See what effect it has on the machine if you switch it in without having the three necessary conditions fulfilled; for instance the voltage of the machine not brought up to the proper value, the machine not in phase with the supply voltage, etc. As this, however, amounts to a partial or even dead short-circuit, be sure that your machine is properly protected by a reliable circuit breaker, which will instantly open the circuit.

(6) Vary the field current of the driving motor and gradually convert it into a generator, "pumping" power back into the D. C. supply. Take a curve showing D. C. and A. C. input and output as a function of this field current.

(7) Investigate the effect of varying the field of the alternator, on the production of wattless currents.

In your report give the following results:

(1) State how long you think it should take an experienced man to synchronize the alternator on which you were working, when using lamps or a voltmeter, or with a synchronism indicator.

(2) Describe what you observed when closing the main switch of the alternator, without having it properly synchronized.

(3) Plot to motor field current as abscissae: D. C. and A. C. currents, volts and watts. In plotting watts consider the input positive and the output negative, or *vice versa*. Plot the efficiency curve of the set, as a ratio of output to input.

(4) Plot to alternator field current as abscissae the results of the experiment (7), as explained above. Plot total alternator current, watts, working component of the current, its wattless component and the current input into the driving motor. Give an explanation of these curves.

ELECTRICAL RELATIONS IN THREE-PHASE CIRCUITS.

This exercise is intended for an experimental study of relations in polyphase circuits and also for familiarizing the students with the methods of measuring current, pressures and power in such circuits. The fundamental facts about polyphase currents are supposed to be known, but it may be well to recall here the origin of these systems and to make a short review of their applications.

A simple alternating current is entirely satisfactory for lighting, but up to this time the inventors have been unable to construct a satisfactory single-phase motor for ordinary commercial work. The single-phase commutator-motor is well adapted for railway work only, and the single-phase induction motor, although used to some extent, is not a very good machine except in small sizes. But if the actions of *two or more alternating currents differing in phase are combined in one motor,* the motor can be very much improved, because then *at no time is the power equal to zero* in all component circuits or phases at once.

Such combinations of several alternating currents mutually interlinked into one system, are called *polyphase systems,* and their origin was a demand for a good alternating current motor. The motors used on polyphase circuits are: induction motors, based on the familiar principle of the revolving magnetic field, and synchronous motors, which are polyphase alternators operated as motors.

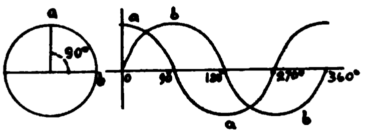

Fig. 1.

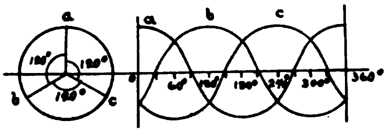

Fig. 2.

Of all possible combinations of alternating currents only two simplest ones came into general use: the *two-phase system,* consisting of two currents with a phase displacement of 90°, or quarter of a period (Fig. 1), and the *three-phase* system consisting of three currents symmetrically displaced in phase by 120°, or one-third of a period (Fig. 2).

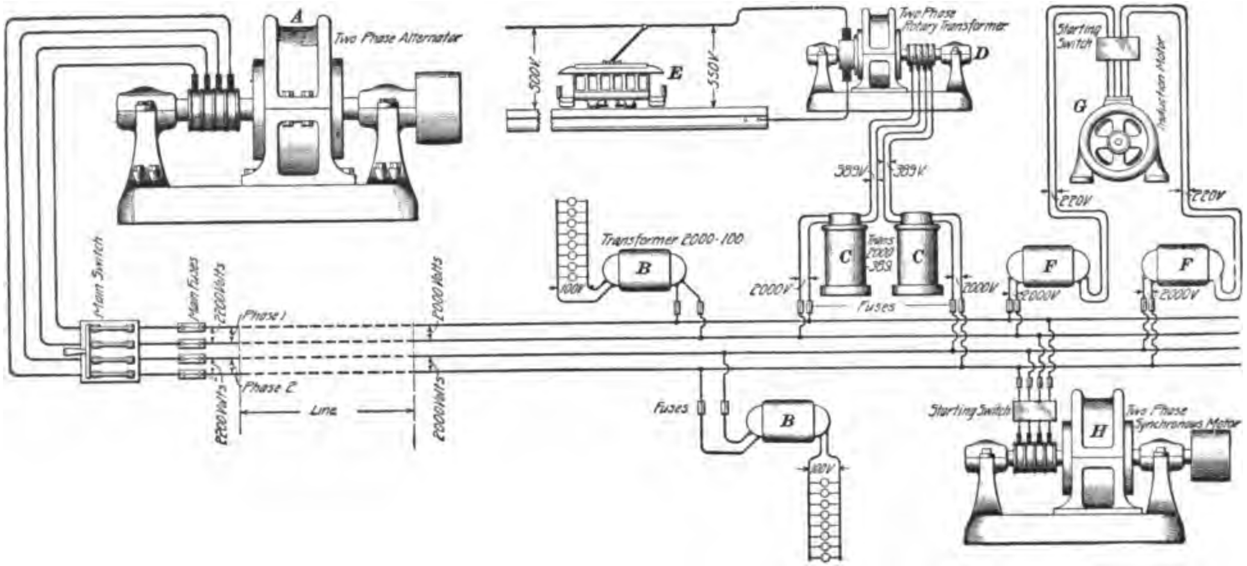
A
Two Phase Alternator
Main Switch
Main Fuses
2200 Volts
Phase 1
Phase 2
2200 Volts
Line
2000 Volts
2000 Volts
500V
E
550V
Two Phase Rotary Transformer
D
389V
389V
Transformer 2000-100
B
100V
2000V
C
Trans 2000 389
C
Fuses
2000V
F
2000V
F
2000V
220V
220V
Starting Switch
G
Induction Motor
Fuses
B
100V
Starting Switch
H
Two Phase Synchronous Motor

Fig. 3.

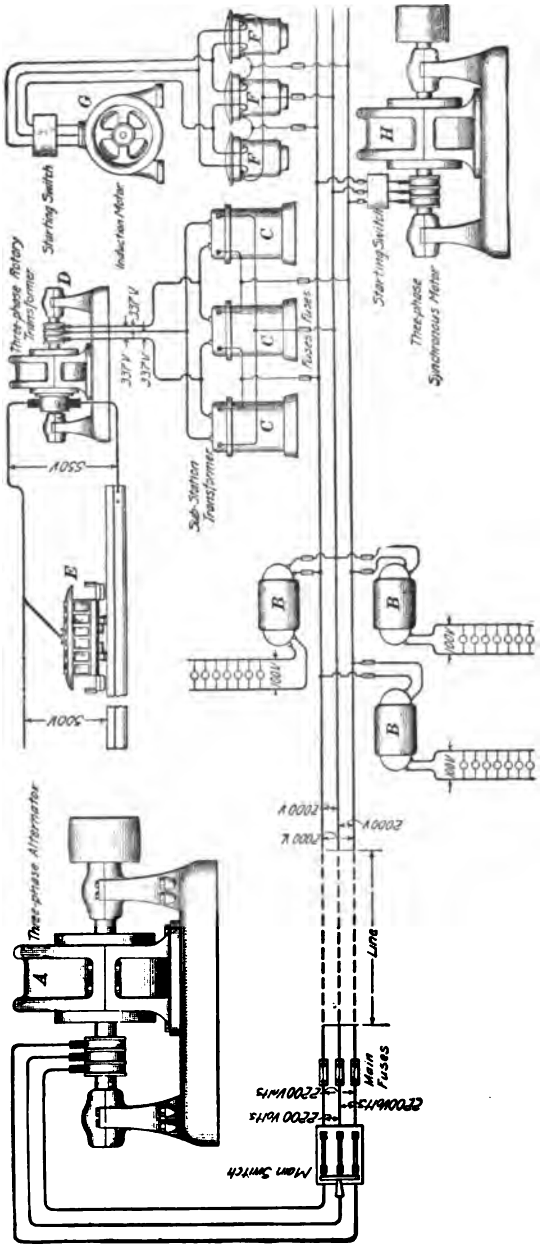
Three-phase Alternator
A
Main Switch
2200 Volts
2200 Volts
Main Fuses
Line
2000 V
2000 V
2000 V
300 V
E
550 V
B
B
B
100 V
100 V
100 V
Sub-Station Transformer
C
C
C
Fuses
337 V
337 V
337 V
Three-phase Rotary Transformer
D
Induction Motor
Starting Switch
G
F
F
F
H
Starting Switch
Three-phase Synchronous Motor

Fig. 4.

Figs. 3 and 4 show practical applications of two- and three-phase currents for power transmission, lighting and railway work. The letters are the same on both sketches: *A* is a polyphase generator supplying currents to a 2200 v. transmission line; *BB* are lighting transformers stepping down the voltage to 100 v. for incandescent lamps; *CC* are transformers for the rotary convertor *D,* which transforms the alternating into 500 v. direct current for street cars *E*; *FF* are transformers for an induction motor *G*; a synchronous motor *H* is also shown, operating direct on 2200 v. without step-down transformers.

It is not absolutely necessary, however, to use low voltage for induction motors and high tension for synchronous motors. Induction motors can be operated on high voltages just as well, and synchronous motors can be operated through step down transformers. As a rule it is safer to operate small motors on low-voltage lines, while large motors installed in separate rooms and having a special attendant can be operated safely enough on a high tension line, thus saving the cost of step-down transformers.

The understanding of electrical relations is much easier in the two-phase system than in the three-phase system because the former can always be considered as a combination of two simple alternating-current circuits; volts, amperes and watts can be measured in each phase separately. For this reason and also because the three-phase system is used for power transmission almost exclusively, this exercise is limited to a study of the relations in the three-phase system.(*)

Two schemes of three-phase connections are mose commonly used: the star or "Y" connection (Fig. 5) and the "Δ" (delta) or triangle

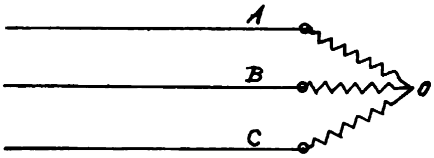

Fig. 5.

connection (Fig. 6). Both schemes are used in practice, and though there are cases when one or the other kind of connections is preferable,

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[*] **The two-phase system has certain advantages when electric power is distributed mainly for lighting.**

as a rule both can be used equally well in the majority of cases. The *pros* and *cons* in this question would hardly interest the student at this stage of his knowledge, and are therefore omitted. It is merely desired that he should make clear to himself current, voltage and power relations in these two schemes of connections.

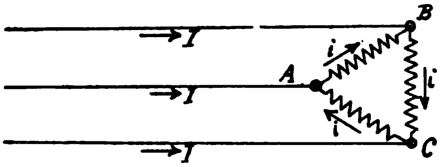

Fig. 6.

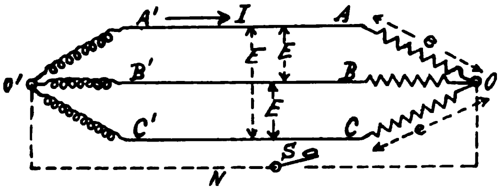

Fig. 7.

(1) *Y-connection* (Fig. 7). Suppose *OA, OB* and *OC* to be three resistances connected in "*Y*" and constituting the load of a three-phase system. Let *O'A', O'B' and O'C'* be the corresponding armature windings in which the three-phase currents are generated. The currents are relatively displaced by 120°, as shown in Fig. 2. It may seem at first that a fourth wire such as *ONO'* is necessary as a common return conductor for the phase currents. Experience and theory show, however, that this conductor is not necessary since the sum of the three phase currents is identically zero at all momemts (at least when the load is balanced, and the currents vary exactly according to the sine law).

The easiest way to see this is to add point by point the ordinates of the three curves shown in Fig. 2. It will be seen that their sum is equal to zero for any instant of time. This is a direct result of a mathematical proposition that the sum of sines of any three angles differing by 120° degrees from each other is equal to zero. That is to say

$$Sin\ x + Sin\ (x + \tfrac{1}{3}.2\ \pi)$$
$$+ Sin\ (x + \tfrac{2}{3}.2\ \pi) = O.$$

When the load becomes unbalanced or the currents do not vary exactly according to the sine wave, currents would flow through this return wire. Actual experience shows, however, that in practice, these currents never attain any considerable magnitude, so as to necessitate an extra conductor. All that is required is to have the points O and O' connected to the ground; the equalizing currents find their way through the ground.

Two kinds of voltages are distinguished with the Y-connection: phase voltages e, such as between O and A, or O' and A', etc., and line voltages E such as AB, AC and BC. Theory and experiment show that

$$E = e\sqrt{3}.$$

This is because the voltage between say A and B is a difference of the voltages O-A and O-B, or

$$e\,Sin\,x - e\,Sin\,(x + \overset{1/3}{\cancel{1-3}}.2\,\pi)$$

which is $= e\,\sqrt{}\;Sin\,(x - 30°)$, so that apart from the phase displacement of 30° the amplitude of the voltage E between A and B is $\sqrt{3}$ times greater than that between A and the neutral point O.

Total power W delivered to the three resistances is the sum of the watts developed in each phase, or $W = 3Ie$, where I and e now designate *effective* values, and not amplitudes. As the neutral point is not always accessible, it is customary in practice to figure out the power by using the line voltage E instead. With the above relation $E = e\sqrt{3}$

$$W = EI\sqrt{3}.$$

If there is some phase displacement between the currents and the voltage e due to the resistances being inductive, the above expression must be multiplied as in single-phase circuits by $Cos\phi$ and we have

$$W = EI\sqrt{3}\,.\,Cos\,\varphi.$$

There are two ways of connecting wattmeters for measuring power in three-phase circuits: the three-wattmeter method (Fig. 8) and the

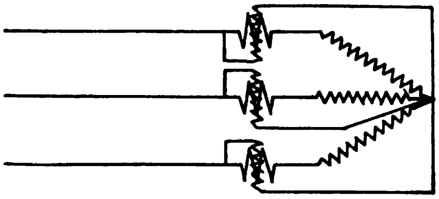

Fig. 8.

two-wattmeter method (Fig. 9). The first method is self-evident: the power is measured in each phase separately and the results added together. This method gives correct results for total power under all circumstances, whether the load is balanced or not.

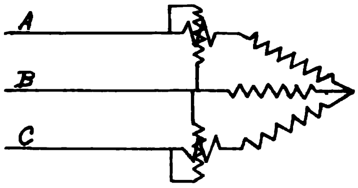

Fig. 9.

The two-wattmeter method is the one generally used in practice, since the neutral point *O* is not always accessible, and also because with this method only two wattmeter readings are necessary instead of three. This method is based on the assumption that any of the three wires can be considered as a return wire for the currents flowing in two other wires. With the connections shown in Fig. 9 wire *B* is taken as the return wire, so that the three-phase system is reduced to two single-phase systems *A-B* and *C-B*. The power in the first system is equal to the current in *A* times the voltage between *A* and *B*. The power in the second is similarly equal to the current in *C* times the voltage between *C* and *B*. The wattmeters shown in Fig. 9 are connected so as to measure the power according to these expressions. The total power is equal to the sum of two simultaneous wattmeter readings, and the method is also correct for balanced as well as for unbalanced loads.

The following remarks on the two-wattmeter method will make easier its practical application:

(*a*) The two component readings are equal to each other only with balanced non-inductive loads; under all other conditions they are different. When the power factor is below 50%, one of the wattmeters begins to give negative deflections. If this is the case reverse either its current or voltage terminals and then take a difference of the two readings instead of their sum.

(*b*) It does not make any difference which of the three wires is selected as the return wire; it affects only the component readings, but not the sum which represents the total power in the system and is always the same for a certain load.

(*c*) It is not always convenient to have two separate wattmeters and to read them simultaneously. Polyphase wattmeters are on the market for this purpose; they consist of two ordinary wattmeters having moving elements mounted on a common shaft, so that the indications are automatically added together; the pointer reads on the scale the total power. The connections are made as in Fig. 9.

(*d*) Where a polyhase wattmeter is not available it is still possible to use one wattmeter instead of two, by having double-throw switches arranged so that this wattmeter can be switched over from one phase to the other. This of course is permissible only when the load is steady, while the wattmeter connections are being changed.

(*e*) If the load is perfectly balanced it is sufficient to measure the power in one phase only as shown in Fig. 10, and to multiply the results by 3. It is assumed in Fig. 10 that the neutral point of the load is not accessible; therefore an *artificial* neutral is created by connecting three high resistances or inductances in *"Y"* and connecting the potential winding of the wattmeter between one of the line wires and this neutral. If the neutral point of the generator or load is accessible, this complication is of course unnecessary.

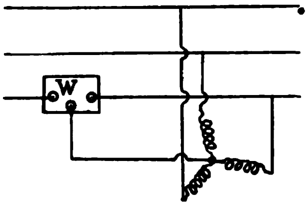

Fig. 10.

2. *Delta connection.* This scheme is diagramatically represented in Fig. 6. Fig. 11 shows the connections when each phase is loaded

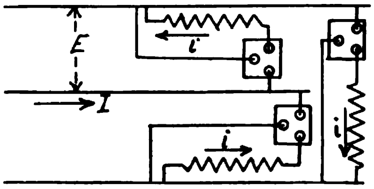

Fig. 11.

separately, for instance if the load consists of incandescent lamps. Electrically of course the schemes shown in Figs. 6 and 11 are equivalent. Delta connection differs from the "*Y*" connection in that there is no neutral point in the former and the phase load is subjected to the full line pressure *E*. On the other hand with "*Y*" connection each phase consumes the full line current *I*, while in a delta connected load the current *i* in each phase is only $1 \div \sqrt{3}$ of the line current *I*. This can be proved in exactly the same way as was proven before than $E = e\sqrt{3}$. Namely, with the positive directions of the currents as shown in Fig. 6 we have, that current *I* in the line wire *A* is a difference of the currents *i* in *AB* and *AC*. This difference is

$$i \, Sin \, x - i \, Sin \, (x + 1/3 \, . \, 2 \, \pi) = \sqrt{3} \, . \, i \, Sin \, (x - 30^\circ).$$

so that apart from the phase relations the current $I = i\sqrt{3}$.

Suppose that a three-phase alternator is loaded so as to supply a certain line current *I* at a voltage *E* between the line wires; and suppose that we arrange the load first in "*Y*" as per Fig. 7 and then in delta as shown in Fig. 6. The resistances of the load are supposed to be adjusted so that we have the same *E* and *I* in the line in both cases. With the "*Y*" connection each phase resistance consumes current I at a pressure $e = E \div \sqrt{3}$, or a power equal to $IE \div \sqrt{3}$. With the delta connection each phase consumes a current equal to $I \div \sqrt{3}$ at a voltage equal to *E* or again the same power $IE \div \sqrt{3}$. The total power *W* in the three phases is also the same in both cases and is equal to $3 \times EI \div \sqrt{3}$, or $EI.\sqrt{3}$, as was proven before.

The three-wattmeter method can be used with the delta connection as shown in Fig. 11, where the power is measured separately in each phase, or the two wattmeter method as in Fig. 9. In fact *when the two-wattmeter method is used it is not necessary to know which way the load in connected, since one of the line wires can always be assumed to be a return wire for two other line wires.* The single wattmeter method as shown in Fig. 10 can also be used equally well, provided of course that the load is balanced in all three phases. Such is the case when the load consists of three-phase motors exclusively.

The students are given in the laboratory a special alternator, which can be connected at will single-phase, two-phase or three-phase. The necessary inductive and non-inductive resistances, measuring instruments,

etc., are also provided, and the exercise consists in loading the alternator on resistances connected in "Y" and in delta. The numerical data observed will make clear the fundamental current, voltage and power relations explained above.

It would be rather cumbersome to have all the necessary ammeters, voltmeters and wattmeters for each phase; more than that, the results would not be directly comparable unless the instruments be in exact calibration. Therefore a special "polyphase board" is provided with switches so arranged that the same instrument can be connected in succession in all three phases without opening the main circuit. With this device one ammeter, one voltmeter and one wattmeter are sufficient for all measurements.

The experiment can be conveniently performed in the following order:

(1) *Y-connection.* Have the alternator "*Y*"-connected and load it on three resistances also "*Y*"-connected, as in Fig. 7. Adjust the resistances so as to have the same current *I* in the three phases, and verify the following facts:

(*a*) The sum of the three currents on balanced load is identically zero: to prove this insert an ammeter into the neutral wire; if the phases are well balanced the ammeter hardly shows any deflection. Moreover, opening and closing the switch *S* in the neutral does not affect the ammeter readings in the three phases.

(*b*) There is no difference of potential between *O* and *O'*, so that both these points can be permanently grounded.

(*c*) Now unbalance the load; immediately a current will flow in the neutral if the switch *S* is closed. Take readings with the switch *S* open and closed with the same load resistances. You will see that the neutral tends to keep the three phase voltages *OA, OB* and *OC* equal. Without the neutral they are different and there is also a difference of potential between O and O'.

(*d*) Verify the fundamental relation $E = e\sqrt{3}$, by measuring all the voltages at a balanced load.

(*e*) Measure the power by the two-wattmeter method and the three wattmeter method and show that both give the same results on balanced as well as on unbalanced loads; also that the result does not depend on which phase is selected as the return wire.

(*f*) If time will permit, arrange a balanced *inductive* load and

show that in this case the component readings according to the two wattmeter method are different, those with the three-wattmeter method are equal to each other, and still the total power measured by either method is the same. If possible, reduce the power factor of the load below 50% and prove that in this case the difference of two readings and not their sum represents the total power. This can be done as before by measuring the power according to the three-wattmeter method.

(2) *Delta connection.* Connect three non-inductive resistances as per Fig. 6 or 11 and adjust them so as to have the same currents in the three phases. The generator can be left Y-connected as before, or the connections can be changed to delta. This will not make any difference in this case, since we are here concerned with the load and not with the alternator. Make the following measurements:

(*a*) Prove that the ratio between the currents I and i is equal to $\sqrt{3}$, or at least is very near it.

(*b*) Prove that the power here can also be measured by the two-wattmeter method with balanced as well as with unbalanced loads. This is done by measuring the power directly in each phase as per Fig. 11 and comparing the sum of the three readings to the sum of two readings according to the two-wattmeter method.

(*c*) Unbalance the load in one of the phases and see how it affects the currents and the voltages in all three phases. It will be found that with delta connection the phases are more independent of each other than with Y-connection (without the neutral wire).

In your report give the results of all the above tests and explain in how far they corroborate the theoretical conclusions about the three-phase system.

NOTE. The relations in polyphase circuits are somewhat more complicated than in ordinary direct-current or single-phase circuits; the beginner sometimes encounters difficulties in understanding current, voltage and power relations in polyphase circuits, particularly in their application to the most important practical question with which an operating engineer is most likely to deal, viz., figuring out the size of conductors for a two-phase or a three-phase transmission line.

The necessary explanation as to how a three-phase or two-phase line can be reduced to an equivalent single-phase line and calculated as such is given in the Note on transmission lines (p. 14); a few remarks may

be proper here, since polyphase lines can also be figured out directly from the relations derived above.

The problem usually presents itself in some such form as this: 500 K. W. is to be transmitted by means of the three-phase system over a distance of 4 miles with a loss of 8% of the power delivered; the pressure at the receiving end of the line is to be 6600 v. What is the size of conductors to be used?

Let us first assume that the load is non-inductive; the current in each wire is then according to the formula $EI.\sqrt{3}$, equal to $\frac{500}{6.6 \times \sqrt{3}}$ $= 43.8$ amps.;(*) the loss of power allowed in the line is $0.08 \times 500 = 40$ kilowatts, or $40{,}000 \div 3 = 13{,}333$ watts in each wire. The resistance R of the wire can be determined from the equation $I^2R = 13{,}333$, from which we find $R = 6.95$ ohms. The resistances are usually given in wire tables per 1000 feet; the resistance of our wire per 1000 feet must be $\frac{6.95}{4 \times 5.28} = 0.329$ ohms, which, according to the wire table, corresponds to about No. 5 Brown & Sharp gauge.

If the load is inductive, the power factor being, say 80%, a heavier wire will be required because it takes a larger current to produce the same power at a lower power factor. As the loss in the line is proportional to the square of the current, the resistance per 1000 ft. now has to be $0.329 \times (0.80)^2 = 0.210$ ohms; this corresponds to about No. 3 B. & S. wire.

If the transmission is to be effected by means of the two-phase four-wire system the size of the wire is figured out as follows: with 500 K. W. transmitted by two phases, each phase transmits 250 k. w., and the line can be calculated as a single-phase line of the same voltage, transmitting 250 K. W. The current at non-inductive load is $250 \div 6.6 =$ about 38 amperes and the resistance of the line $R = \frac{0.08 \times 250{,}000}{38^2} = 13.9$ ohms. This gives $\frac{13.9}{5.28 \times 4 \times 2} = 0.329$ ohm per 1000 feet, or the same size of wire as figured above for the three-phase system. This result shows that there is a saving of about 25% in copper with the three-wire system as compared to the two-phase system because the size of the wire

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*** The power being given in *kilowatts*, it is convenient to measure the pressure in *kilovolts:* 6600 volts = 6.6 kilovolts.**

being the same in both cases, there is one wire less with the three-phase system.

It may take a certain effort of thought on the part of the student to grasp the fundamental relations set forth in this exercise; it will, however, pay him to do his best to obtain a clear understanding of the three-phase system, at least within the scope of this instruction, which hardly covers the elements of the question. The three-phase system is now practically the only system used for long distance transmission; it is also frequently used for railway work between the power house and the sub-stations. There would be a serious lack in the professional training of an electrical and even a mechanical engineer who had not at least a slight knowledge of the ordinary three-phase system, its advantages and the electrical relations in it. There is but little chance, in practice, to experiment with high tension polyphase currents, and the students should take full advantage of the opportunity offered them in the laboratory.

TELEPHONE WORK.

HOUSE AND INTERCOMMUNICATING TELEPHONES.

The construction of telephone apparatus and the schemes of connections vary widely with the purpose and the distance for which the telephone is used. It is plain enough that a telephone set that works satisfactorily between the kitchen and the dining room of a residence would hardly be suitable for city telephone exchanges and would not talk at all on long-distance lines, say between New York and Chicago. From the standpoint of the distance covered and importance of the service, telephones can be subdivided as follows:

(1) House telephones in residences, offices, etc., where there are only two instruments a few rooms apart and directly connected by two wires.

(2) Intercommunicating systems, as in large offices, factories, schools, hotels, etc., where there are several instruments installed and where it should be possible to have any two connected for conversation.

(3) City and long-distance telephone systems, covering many miles of ground and serving hundreds and even thousands of subscribers.

With the first class of telephone systems no central station or exchange is needed. With intercommunication systems, central switchboard and operator can also be dispensed with if the number of instruments is not more than say 20. With the city and long-distance phones, a central station and operators constitute an indispensable part of the system. This exercise is an experimental study of the construction and connection of telephones of the first two classes, where no operator or central switchboard are necessary.

The two most essential parts of every telephone apparatus are the receiver and the transmitter. A typical receiver is shown in Fig. 1.

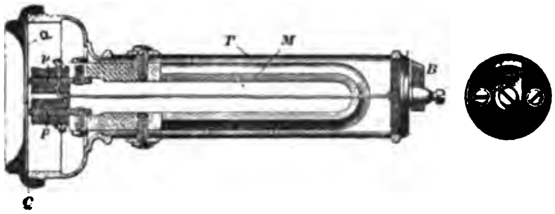

Fig. 1.

It consists of a sheet iron diaphragm, *a,* placed near the poles, *p,* of a steel magnet, M. The poles are surrounded by coils of wire, through which pass the incoming "talking" currents. These small variable currents correspondingly change the magnetism in pole-pieces and cause the diaphragm to vibrate, thus producing the sounds spoken at the sending station. The poles are made of very soft iron in order that they will more easily respond to changes of magnetism, while the magnet, *M,* itself is of hardened steel so as to retain the initial magnetism unaltered with time. The magnet is enclosed in a hard-rubber tube, *T;* the diaphragm is protected by the hard-rubber cap or ear piece, *C.*

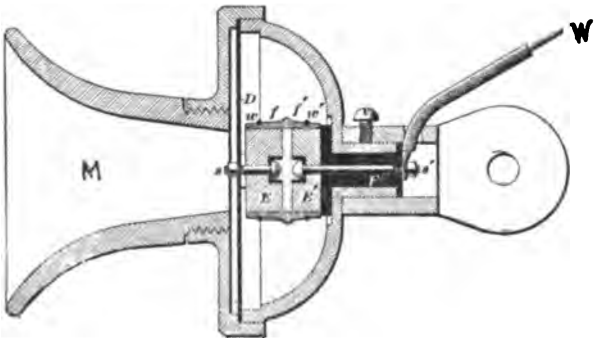

Fig. 2.

A telephone transmitter is shown in Fig. 2. Its principal part is a chamber between carbon blocks, *E* and *E'*, filled with granular carbon. The front block is fastened to the diaphragm, *D,* the other

is connected to the wire, *W*, and insulated from the case of the transmitter by a bushing, *F*.

When sounds are produced before the mouthpiece, *M*, the diaphragm vibrates, and the block, *E*, accordingly presses more or less on the granulated carbon. The current from a local battery passes from the wire, *W*, through *E'*, granulated carbon, *E*, and the diaphragm, whence it passes to the other telephone station through another wire connected to the case of the transmitter. Variations of pressure on the granulated carbon produce changes in its ohmic resistance, so that the current sent through it becomes a rapidly pulsating current; these pulsations act on the diaphragm of the receiver, as was explained before, and so reproduce the speech.

In addition to a transmitter and a receiver, each telephone set is supplied with a bell, a ringing device, a hook switch for changing from ringing to the talking circuit, and frequently an induction coil. The latter is an ordinary small transformer; its primary being connected to the local transmitter-battery circuit and the secondary to the line. With this arrangement only small alternating currents are sent to the line instead of the whole battery current, and their voltage is considerably increased.

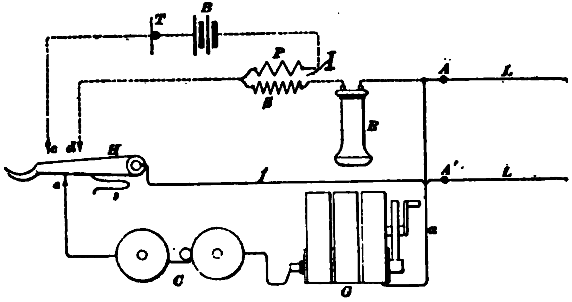

Fig. 3.

Figs. 3 and 4 represent a simple scheme of telephone connections with the receiver on and off the hook. In these sketches *T* is the transmitter, *R* the receiver, *B* the battery, *I* the induction coil and *H* the hook-switch. *G* is a small magneto-generator for calling

up the other party and *C* is an electric bell for indicating calls; *LL'* is the line.*

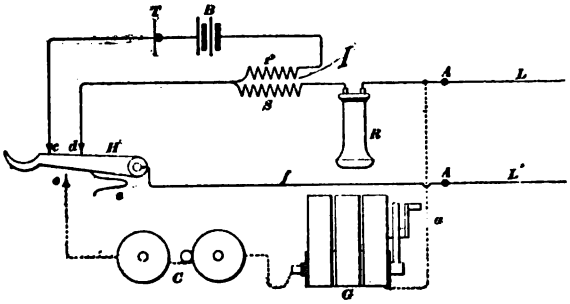

Fig. 4.

When the receiver is hanging on the hook (Fig 3) the receiver and the transmitter circuits are open at *c* and *d;* the ringing circuit is closed at *e* so that this subscriber can be called up by the other party or by revolving the handle of the generator he can call the other party. When the receiver is taken off the hook (Fig. 4), the spring *s* forces the hook up and closes the receiver and transmitting circuits, at the same time opening the ringing circuit. Now the local transmitter circuit is closed through *B, T, c, d,* and the primary *P* of the induction coil. The line circuit is closed through *L, R,* secondary *S of the induction coil, d, H, f, A',* and the line *L';* the apparatus is ready for either speaking or listening.

A magneto-generator (commonly called *magneto*) and a bell are shown in Figs. 5 and 6. Magneto-generator used for telephone service is an alternating-circuit machine, so that an ordinary electric door-bell would not ring with its current. The bell shown in Fig. 6 is a polarized bell; it has a permanent magnet *N'S',* and soft-iron cores *f* and *e* connected by yoke *y.* Yoke is also of soft iron and so pivoted that its ends may move toward either *f* or *e,* according to which is the stronger magnet. Alternating currents from the mag-

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*Most of the modern city telephone systems are built on the "common battery" principle, with which subscriber sets need not have either local battery or magneto or push button for calling up. As soon as the receiver is taken off the hook a small lamp lights up on the central switchboard, calling attention of the operator. Current for the transmitter is also supplied from the central station (hence the name *common battery system*), and when the connection is made, the operator herself calls up the other party. A description of such system is outside the scope of this paper, which deals with simple interior telephones.

neto periodically increase and decrease the magnetism in one or the other leg of the soft iron circuit by adding to or weakening the magnetism induced in e and f by N′S′, so that one end of *a* is attracted more strongly than the other, which makes the hammer strike alternately the two gongs.

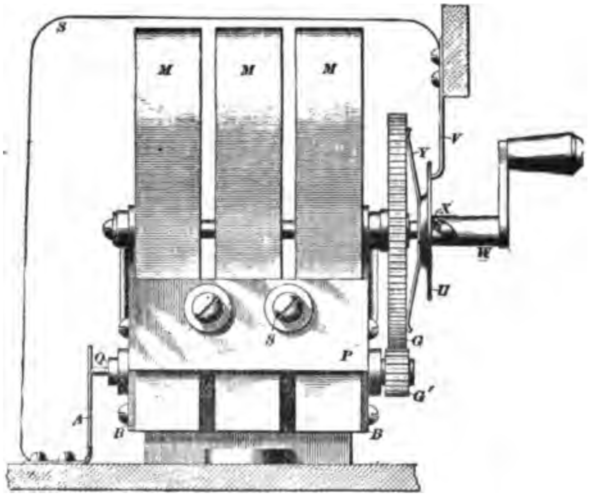


Fig. 5.

One detail in the construction of the magneto deserves mention. When the ringing current comes from the line, it meets on its way (Fig. 3) the resistance of the armature of the magneto, which resistance is quite considerable and unnecessarily weakens the ring-

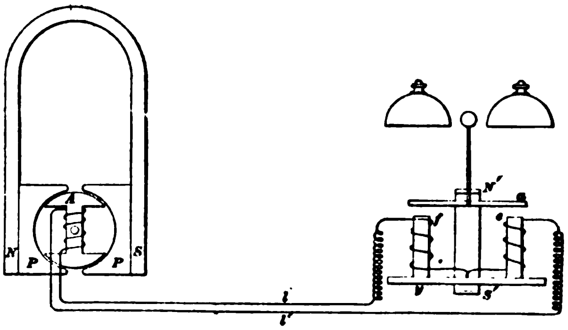


Fig. 6.

ing current. To remedy this, magnetos are provided with special devices that short-circuit the armature when magneto is not in use, and automatically remove the short-circuit as soon as the handle is rotated. One of such devices is shown in Fig. 5; short-circuit is made between the plate *U* and the spring, *V*, to which the plate is pressed by the spring *Y*. When the crank of the generator is operated, *U* is pressed away from *V* by means of the pin *X* riding on the inclined sides of the slot in the sleeve, *W*. As soon as the hand is removed from the crank, the spring *Y* presses the collar *U*. again into contact with the spring *V*, thus re-establishing the short-circuit.

A magneto with a polarized bell is an unnecessary complication on telephones used for very short distances, say between two adjacent buildings. An ordinary battery bell can serve the purpose just as well, at the same time being less expensive and more convenient, as it requires only pushing the button instead of turning the crank. So with house telephones, ordinary battery bells are mostly used; the scheme of connections remains nearly the same, except that the same battery is to be connected into the ringing and the talking circuit; this is accomplished by means of suitable contacts on the hook switch.

We have in our laboratory two telephone sets, one with magneto call, the other with battery bell; the students are to connect up these telephones and try them for conversation. Glass covers are provided on some of the telephones so as to make easier the study of connections inside of the apparatus. The connections may differ in details from those shown in Figs. 3 and 4, but with a clear understanding of the above scheme, following up the the actual connections will hardly offer any difficulty.

After this has been done, the students should try *to adjust* a telephone receiver and a transmitter so as to get the best speech obtainable. Special transmitter and receiver are provided for this purpose and can be taken apart for readjustment. The transmitter is adjusted by varying the amount of the granulated carbon and the pressure on it; besides which the quality of speech depends on the magnitude of the current flowing through the instrument. The receiver can be adjusted by varying the distance between the pole pieces and the diaphragm. A well adjusted receiver should be used for listening while the transmitter is being adjusted, and *vice versa*.

In addition to the above sets, two sets are provided adapted for *intercommunication* service. The students should connect them up

and make clear to themselves the principle of selective ringing and talking between any two instruments.

One of the telephones has in addition to the ordinary parts a dial with 10 buttons and a lever that can swing upon them; if it is desired to speak, say with subscriber No. 5, the lever is set on the button No. 5 and pressed against it. This rings the bell of telephone No. 5, after which the conversation is conducted in the usual manner. In the other set plugs and receptacles are used for selective talking and ringing.

For ten subscribers, 10 wires must be run to all the telephones, and two extra wires—the common return wire and the ringing wire. In one of the sets a common battery is used for ringing, while each subscriber's apparatus is provided with its own transmitter battery; this is done because more cells are usually required for ringing than for talking. The other set has a common battery for talking also.

The exact scheme of connections in these telephones can be easily followed in the apparatus iteslf; as in other telephones, when the receiver is hanging on the hook, the ringing circuit can be closed from any other apparatus, or the ringing circuit of any other set can be closed from this apparatus. When the receiver is off the hook, the talking circuit is closed through the common return wire, and the wire corresponding to the button on which the lever is set.

A drawback of many intercommunicating telephones is that if the person forgets to set the lever back to zero after ending the conversation, it becomes impossible to call him up. In one of the abovementioned telephones, however, an ingenious switch is provided, which automatically returns the lever to zero when the receiver is hung on the switch.

Blue prints are provided in the laboratory, which give all the necessary information for connecting up these intercommunicating telephones. As we have only two sets of apparatus of each kind, ordinary bells must be used in addition, to represent the lacking subscriber sets. By connecting these bells into the circuit selective ringing can be tried, and the connections checked. It is expected that the students will not only blindly make the connections according to the blue prints, but also will try to understand them.

References:

Short explanations given in this note are sufficient for adjusting and connecting the telephones in the laboratory. Those more espec-

ially interested in telephone work may consult the chapters on interior telephone systems and on intercommunicating systems, in Foster's Pocket Book. Popular books on telephony are those by G. W. Wilder and J. E. Homans; see also chapters on telephony in the International Library of Technology and in the Cyclopaedia of Applied Electricity. More complete and advanced treatment of the subject can be found in works on telephony by Kempster Miller and A. V. Abbott. All of the above named books can be found in the University Library.

SHUNT MOTOR.

FIELD CONTROL AND THREE-WIRE SYSTEM.

Until very recently the method of power transmission in shops consisted of a series of shafts and belting, taking power from the engine or turbine as a prime mover and transmitting it to individual tools. The disadvantages of such a system in application to large modern industrial establishments are apparent; it required a separate steam engine in nearly every building, and at times a big engine would run at a very light load. Moreover, if but one boiler house were installed for the whole factory, condensation losses in the piping system were considerable; on the other hand, if two or more boiler houses were put in, there was evidently still less economy.

With the advent of the electric motor, the above considerations led to the idea of having a generation plant where electric current can be produced most economically for the whole factory, both for light and power, and installing electric motors in each shop for driving the shafting. This was a step in the right direction, though not the final one; the drawback of a large motor running at times uneconomically on light loads was still there, and complicated and expensive shafting and belting were not yet eliminated. The next step was to use several smaller motors instead of a large one, and to drive separate groups of machine tools or, in some cases even, each tool individually.

This at once relieved the shop of heavy belting and long transmission shafts, affording a more open and better lighted shop, also made it possible to more easily attain for each machine the most economical speed. This disadvantage of the individual drive is that several small motors with their rheostats, switches and wiring, cost more than one large motor; it was sought to outweigh this drawback by offering additional advantages of the individual electric drive. As an important advantage it was shown that the speed of the motor could be varied within comparatively wide limits by purely electric means, thus either eliminating variable-ratio gears and cone pulleys, or increasing the available range of speed.

It soon became evident that the possibility of an easy speed control of a machine tool within wide limits was of great practical importance, and in many cases permitted such an increase in the output of the tool as to make the individual electric drive the most economical solution. Therefore the tendency on the part of the builders of machine tools and makers of electric machinery was to eliminate the mechanical transmission so far as possible and to have electric motors built as an organic part of machine tools *with the widest range of speeds possible by a purely electrical control.*

Such was the origin of the demand for variable-speed motors, and a considerable amount of skill and capital was and is being spent in perfecting such motors and developing new types. From the above it should not, however, be understood that in *all* cases and under *all* conditions, individual drive is more advantageous than the group drive or than driving the whole shop by a steam or gas engine. This is a proposition that has to be decided separately in each individual case. For instance, if there are several identical machine tools running all the time on the same operation, as is the case in factories manufacturing a special article in large quantities, there is no reason why they should not be driven all together by the same motor at a constant speed. On the other hand, if a shop has a very large lathe used at times for widely different classes of work, and also frequently standing idle, the most natural solution would be to have a separate variable-speed electric motor for driving it.. Most practical cases lay between these extremes, and a demand for an expert disinterested opinion on the question of a proper shop drive, even led to the formation of a new class of consulting engineers, some of whom call themselves "modernizing engineers." From the point of view of an electrical engineer, the question of the machine tool drive stands thus: There is a demand on the market for variable-speed electric motors; what are the electrical means for varying the speed and what are the advantages of one method over another? As a partial answer to this question, this exercise offers an experimental study of the two most popular electric methods of speed control of direct-current motors.

Alternating current motors (induction motors) are essentially constant speed motors and are used in shops for group drive only, or where variable speed of a machine tool is not required or may be attained by other means. The only practical *variable-speed* motor

for machine-tool drive is so far the shunt-wound direct-current motor, and to the same this exercise is limited.

From the general theory of the direct-current motor, we know that its speed is proportional to the pressure at the armature terminals and inversely proportional to the magnetic flux in the air gap; this follows from the general formula for the counter e. m. f. induced in the armature: $E = C\, n\, N.\ 10^{-8}$, where C is a constant, n is the speed and N— the useful magnetic flux. *Thus, in order to vary the speed of a shunt motor, either its field current must be varied or the voltage at the armature terminals.* The first method is shown in Fig. 1, in which a regulating rheostat is connected to the field circuit; the second (multi-voltage system) is shown in Fig. 2, and in its simplest form consists in using an ordinary three-wire system. The armature of the motor (not shown in sketch) can be connected either across 250 v., between the two outside wires, or across 125 v. between an external and the middle (neutral) wire. The speed when running on 250 v. circuit, is twice as high as when running at 125 v.; the field of the motor is in all cases connected across the 250 v. line. G is the main generator, and BS is a "balancer set" for dividing the voltage; it consists of two identical machines connected together and running idle between the two outside wires. The third wire is connected between the machines, at *c*, as shown in Fig. 2.

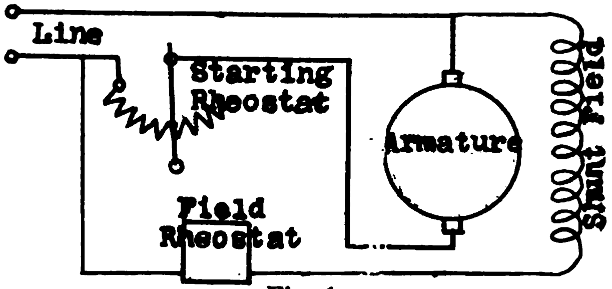


Fig. 1.

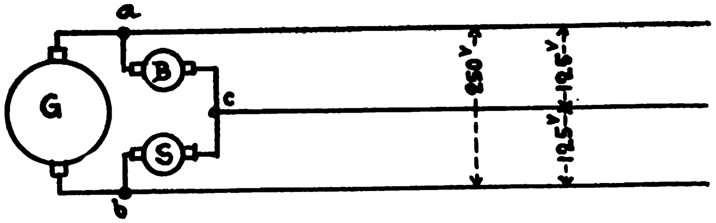


Fig. 2.

Instead of using a three-wire system, two motors can be used driving the same tool or shaft; by connecting them in series or in parallel (as in a street car) half speed and full speed can be had. It is not necessary to have two separate frames and fields; the two armature windings can be put on the same core and revolve in the same field. This is called a "two-commutator motor" (Fig. 3.)

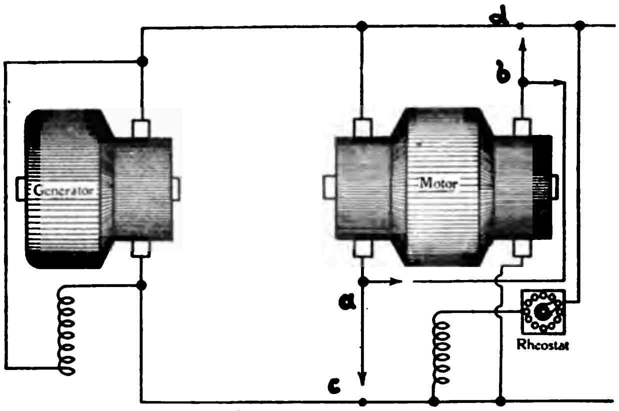


Fig. 3.

When *a* is connected to *b*, the two armature windings are in series and the motor runs at half speed; when *a* is connected to *c*, and *b* to *d*, the two windings are in parallel and the motor runs at full speed. The field circuit is provided with a regulating rheostat by means of which the range of speed is further increased and intermediate speeds are made possible.

We turn now to a more detailed investigation of the first two methods of speed regulation: field control and multi-voltage system.

1. *Field Control.*

A great advantage of the field control over the multi-voltage system is that the motor can be run on any ordinary two-wire line without any balancer set or complication and expense of a third wire. However, with an ordinary shunt motor, a limit is soon reached beyond which the speed cannot be increased because of a vicious sparking at the commutator. This is due partly to the weakened field being distorted by the armature reaction and partly to the increased frequency of commutation. With good modern motors, speed can be increased 100% with the same H. P. output, before this

critical limit is reached (speed ratio 2:1). Motors with a still higher ratio are built, but then it simply becomes a question of rating them correspondingly; for instance a 15 H. P. motor can be sold as a 10 H. P. with a ratio of speeds as 3:1, and with a corresponding increase in price, as compared with a regular 10 H. P. motor.

The armature reaction and the accompanying sparking on the commutator being the cause that limits the increase in speed of a motor, it becomes evident that the efforts of the designers of variable-speed motors were directed towards a possible reduction of the armature reaction. This meant in the first place a strong, saturated magnetic field and a comparatively weak armature (expressed in ampere turns). The next step was to compensate for the armature reaction by providing an auxiliary field (Fig. 4) equal and opposite to that created by the armature. The coils producing this com-

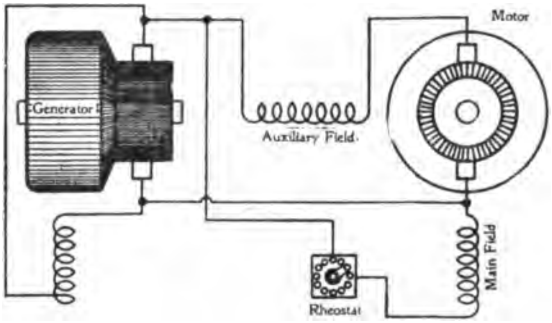


Fig. 4.

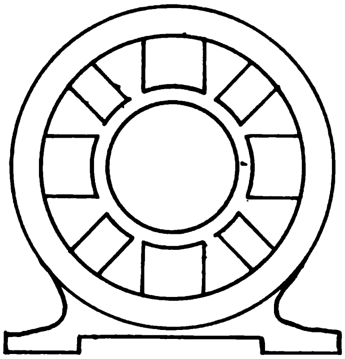
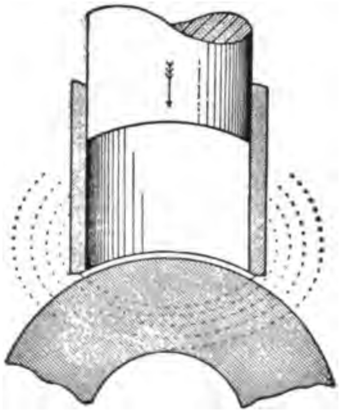


Fig. 5.

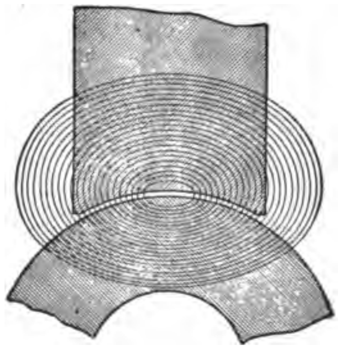
pensating field must evidently be connected in series with the armature circuit so as to always give the right number of ampere turns with varying armature currents. The field of one of the new commercial forms of compensated motors is shown in Fig. 5. The four large poles produce the main field (shunt field), the four small poles constitute the auxiliary field; this so-called "inter-pole" motor gives a speed ratio of 4:1 by field control without excessive sparking.

The field arrangement of another type of variable-speed motor is shown in Fig. 6 (Stow motor). Instead of varying the field strength by regulating the shunt current, the field strength in this motor is varied by varying the length of the air gap. The pole piece is made in the form of a plunger actuated by a hand wheel on the top. The higher the pole piece is raised, the larger is the air gap and therefore the weaker is the field (with the same field current.) In four-pole motors of this type all the pole pieces are moved simultaneously by a beveled-gear transmission. The reason why the armature reaction is reduced in this motor at higher speeds can be seen by comparison of Fig. 6 to Fig. 7, which later represents the field of an ordinary motor. In Stow motor, as the air gap becomes larger, the reluctance of the magnetic path for the armature lines of force (shown by dotted line) also increases, thus reducing the harmful cross-magnetization flux.



POLE PIECE IN STOW MOTOR.
Cross magnetization intercepted by air column.

Fig. 6.



SOLID OR LAMINATED POLE
Field distortion greatest when field is weakest.

Fig. 7.

In another type of motor, based on the same principle, the armature is made slightly larger at one end than at the other, and can be shifted along the shaft. As it is withdrawn from the pole pieces the useful magnetic area decreases; moreover, the air gap increases because of the conical shape of the armature. The result is that the useful flux decreases, and the speed of the motor increases.

The laboratory work with variable-speed motors consists in studying their performance under various conditions of load and speed. Either a Prony brake or a calibrated dynamo can be used as a load. In order to save time and have more runs taken under different conditions, readings on light loads can be omitted. Start at the heaviest load and lowest speed possible; read input, output, speed, etc., as in any regular brake test. Then run the motor light with the same field; this will give its speed variation between full load and no load, and also no-load losses corresponding to this particular value of field current.

Then load up the motor again to its full capacity at a lower field current (higher speed), and repeat the two runs as before; increase the speed again, etc., until the limit of speed is reached, beyond which it would not be safe to go, on account of danger to the motor from the action of centrifugal force and destructive sparking. Remember, that variable-speed motors are usually rated to give the same output at all speeds; this means that the torque must be decreased as you go to a higher speed.

For a comparison, a few similar runs should be taken on an ordinary shunt motor, not intended for variable-speed work within wide limits. It will be seen that the sparking limit will be attained much sooner than with the motors having some device, compensating or keeping down the armature reaction.

From the no-load and full-load readings, values corresponding to intermediate loads can be calculated with a sufficient accuracy, from no-load losses and the resistances of the windings. In this way complete performance curves of at least one motor should be plotted for the report.

2. *Multi-voltage System.*

It can be seen from the foregoing that in order to get the full benefit of the field control, a special, or at any rate a larger, motor must be used, so that a saving in wiring and in the balancer set is to some extent outweighed by an increased cost of the motors them-

selves. Therefore there are cases in which it pays to use the ***three-wire*** system and ***ordinary*** shunt motors; furthermore, by combining the three-wire system with field control, a speed range of 4:1 can easily be attained. To get the lowest speed, say 400 r.p.m., the motor is fully excited and the armature connected to ½ voltage; then by gradually weakening the field, the speed can be doubled before the difficulty in commutation begins; this gives any desired speed between 400 and 800 r.p.m. After this the armature can be switched on to the full voltage and the field again fully excited, which gives 800 r.p.m.; then by weakening the field the speed can be brought up to 1,600 r.p.m.

Instead of using a balancer set (Fig. 2) for dividing the voltage for a three-wire line, two methods are also used, shown in Figs. 8 and 9. In Fig. 8 the voltage is divided by means of a storage battery; in Fig. 9 a special three-wire generator is used. The application of a storage battery is evident without explanation; the three-wire generator is an ordinary direct-current machine provided with three or four slip rings in addition to its commutator, from which three-phase or two-phase (quarter-phase) currents can be taken.

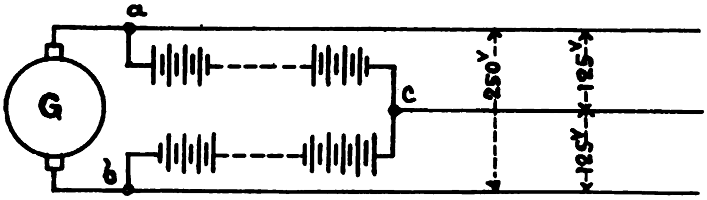


Fig. 8.

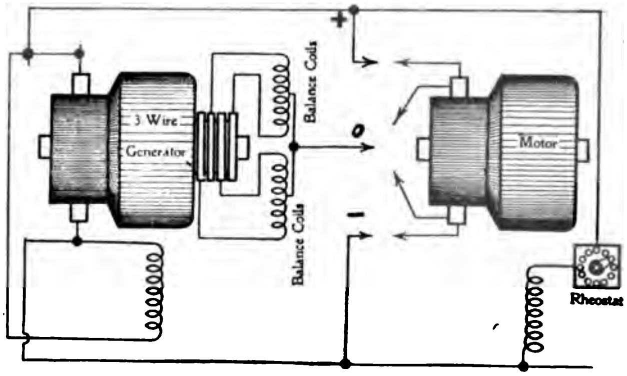


Fig. 9.

The slip rings are connected to inductance coils (so-called balance coils) and the neutral of the three-wire system is connected to the neutral point of this polyphase system. This neutral point being symmetrically situated in regard to both wires of the direct-current side, its potential is midway between the potentials of these wires, and this divides the voltage in two equally. The energy consumption in the balance coils is small, their inductive resistance being large as compared with their ohmic resistance. An advantage of this system over the balancer set is that the balance coils are less expensive than a balancer set and being stationary hardly require any attention. On the other hand, a three-wire generator is more expensive than an ordinary two-wire machine. Here, as in most practical problems, the preference is given in each particular case to one or the other system, according to the sum total of local conditions and the personal views or experience of the engineer who has to decide the question.

It is not necessary to have the voltage divided in two *equal* parts, and in fact by making the system unsymmetrical a wider range of speeds can be obtained. One of such unsymmetrical, or, as they are called, "unbalanced" systems, is shown in Fig. 10. The two

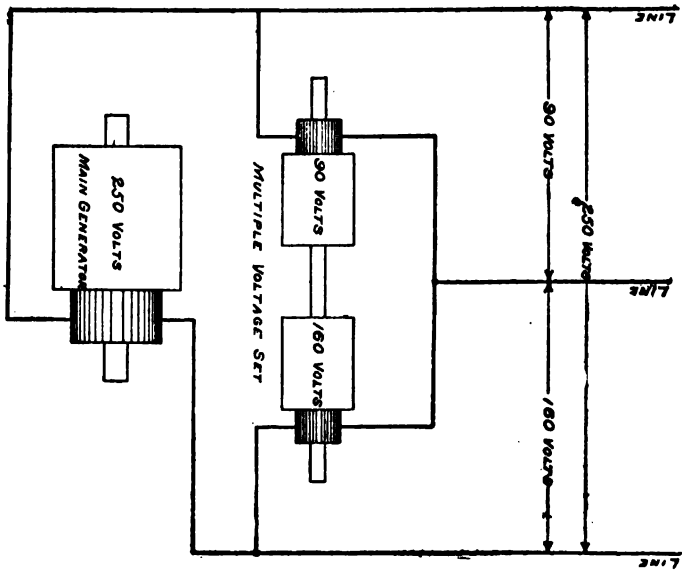


Fig. 10.

machines constituting the balancer set are wound and excited for different voltages so that the total of 250 v. is subdivided into 90 v. and 160 v. With this system the armature can be connected on either 90, 160 or 250 v., which gives a ratio of about 3:1 between the lowest and highest speed. If, in addition, field control is used, a ratio of 6:1 can be had instead of 4:1, as with the symmetrical three-wire system. The disadvantages of this system as compared to the ordinary three-wire system are: a more expensive wiring because the motors take a heavy current at low voltage; the system is unsymmetrical and therefore more difficult to supervise; and the balancer set is more expensive. The application of this system has thus far been a limited one, though it may be profitably used in shops where the widest possible range of speed is of prime importance.

Some companies have gone so far as to use a *four-wire* unsymmetrical system in order to get a still wider variation of speed of the motors. One of such systems that has been practically applied in a few cases is shown in Fig. 11. Here the balancer set consists of three direct-connected machines, A, B and C. Two of these machines can be combined into one two-commutator machines; this makes the set less expensive and cumbersome. It will be seen that with such a system, six different combinations of voltages, and therefore six different speeds are possible without any field control. The ratio of the

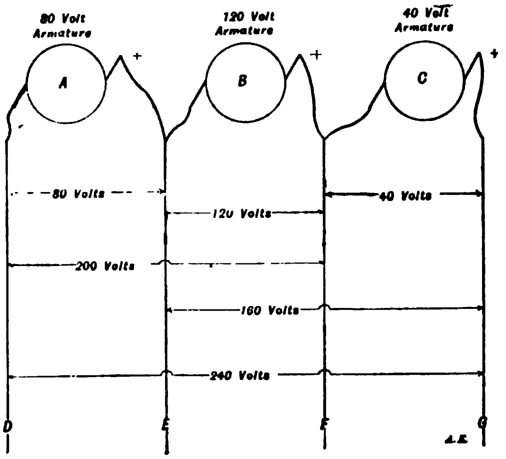


Fig. 11.

highest to the lowest speed in this particular system is as 240:40=6:1; by using field control, the range of speeds can be still more increased. The complication and expense of a four-wire unsymmetrical line is, however, such as to justify the use of this system in exceptional cases only. The more expensive labor and machinery become, the greater the field which will be opened for such multi-voltage systems, as they permit the output of the tools to be increased to the utmost limit.

Laboratory work on the three-wire system consists of two parts: a study of the performance of a motor at various voltages, and a study of the balancer set itself. We have in the laboratory a symmetrical and an unsymmetrical balancer set. Take an ordinary shunt motor (or a compensated motor having its compensating winding disconnected) and run it in succession with both these balancers. Do not attempt to take complete load curves in the time alloted for this exercise, but merely no-load and full-load points. Take a set of readings at full voltage and at partial voltages, both with full field current and with the field weakened. The results when properly tabulated will give a clear picture about the operation of the motor on the balanced and unbalanced three-wire systems.

Then the two balancer sets must be tested in regard to their efficiency and voltage regulation. It would not be practicable to load them on motors for this purpose: a load consisting of resistance frames can be much more conveniently adjusted and kept constant at any desired value.

Take first the symmetrical balancer set and load up one side of the line until the balancer runs as nearly as possible to its full rated capacity. Note the input into the motor and the output of the generator constituting the balancer set, voltages on the loaded and unloaded sides of the line, speed of the set, currents in all line wires, and the field current of the balancer machines. Then begin loading the other side of the line, keeping the load on the first side constant. As the unbalancing decreases the balancer load also decreases though the total load on the line increases. Take readings as indicated above with different degrees of unbalancing until the load on both sides is the same and the balancer runs idle. Increasing the load further merely reverses the conditions in the balancer, the machine which was running as motor will begin to run as generator, and *vice versa*.

A similar test should be performed on the unsymmetrical balancer set. Here, however, the two machines being of a different type

both sides of the line must be loaded in succession, so as to observe the working of each machine as a generator.

References:

The demand for variable-speed motors having arisen comparatively recently, very little can be found on the subject in regular text books. A special meeting of the American Institute of Electrical Engineers, Nov. 21, 1902, was devoted to this question. In the Transactions' report of this meeting.

8235 I 20, pp. 111-213, considerable information on the subject can be found, presented by the leading authorities. It is discussed there by manufacturing, operating and consulting engineers, and though the opinions expressed are not always unbiased, the report deserves most serious attention.

A paper on "Electric Motors in Machine Shop Service" was presented before the last International Electrical Congress in St. Louis, 1904, by Mr. Day. The paper may be found in the Transactions of the Congress.

8235 Z 1904, Vol. II, pp. 590-611; it is also reprinted in

28 A (open shelves) Cyclopaedia of Applied Electricity, Vol. 2, pp. 315-345. The middle part of the paper, entitled "Notes on Motor-Drive Systems" refers directly to the subject of this exercise.

Special pamphlets on machine-tool drive and variable-speed motors have been published by several electric manufacturing companies, each giving the advantages of their own system. Some of these pamphlets can be found in the classified catalogue file in the E. E. Department.

ARC LAMPS.

Whenever evenly distributed electric light in small units is required, incandescent lamps are used. Where, however, cheaper lighting by larger sources of light is sufficient, as on streets, in shops, railway stations, etc., arc lamps are generally preferred.

The purpose of the laboratory exercise on arc lamps is to give the students an opportunity for studying the construction and operation of these lamps and of the auxiliary apparatus used in connection with the same. Accordingly, one laboratory period is scheduled to be spent in experimenting with a few representative types of lamps, and another period in loading an arc machine and an arc-light transformer.

1. *Construction and operating features of arc lamps.*

Arc lamps used at present can be subdivided into direct-current lamps and alternating-current lamps, and also into lamps intended to be used in series and those to be used in parallel. This gives four commercial types of lamps: series direct-current, multiple direct-current, series alternating-current and multiple alternating-current. Multiple type lamps are used for indoor lighting and generally where lamps have to be connected to an existing low-tension network. Series lamps are used for street lighting; as many as 100 lamps can be connected in series on a special high-tension circuit with a very small expense of line copper.

The physical phenomenon of an electric arc between two carbons is so commonly known that it seems hardly necessary to go into detail about it. A direct-current arc is shown schematically in Fig. 1; the upper (positive) carbon forms a "crater," from which light is thrown down, in the direction where it is mostly needed. With the alternating-current arc (Fig. 2) no such crater is formed and the light is distributed fairly equally in all directions, a large amount of it being thereby wasted. Moreover, a direct-current arc gives with the same watts input considerably more light than an alternating-current one. This makes the direct-current arc lamp superior to the A. C. lamp, the more so

since the latter makes an unpleasant humming noise, which may be objectionable in some cases.

Nevertheless, the advantages of energy *distribution* by means of alternating currents are so great that alternating arcs are coming more and more into use. This is especially true for series street-lighting; while it is comparatively easy to produce voltages up to say 10,000 volts by means of alternators and step-up transformers, continuous current machines for such voltages have serious drawbacks because of commutator troubles, and are gradually going out of use. Thus it must be understood that while direct-current arcs are more preferable in themselves, alternating-current arcs afford better current distribution along scattered areas.*

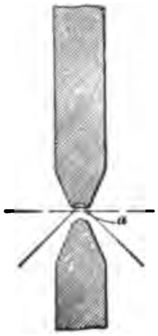


Fig. 1.

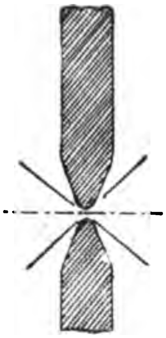


Fig. 2.

The commercial arc lamps used at present are so-called enclosed arcs; the carbons are surrounded by a small globe which practically excludes the air. The advantage of such an arrangement is that with the enclosed arc the rate of consumption of the carbons is much slower. While an open arc lamp requires carbons to be renewed say every 10 hours, or even more frequently, enclosed lamps will burn as long as 150 hours and more. This means a considerable saving in trimming service and carbons. The light

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* A system was recently proposed which claims to combine the advantages of both systems; it is based on the use of mercury-vapor rectifiers. Ordinary alternating current is generated in the power house and if necessary is stepped up by transformers; then it is *converted into direct current* by means of a mercury-vapor rectifier and used for series direct-current arc-lamps. This system apparently has good chances for success, although the mercury rectifier has not yet had a sufficient practical test as to its reliability.

of an enclosed arc lamp is much softer and steadier, and in addition the fire risk in indoor use is less, because the small globe surrounding the carbons prevents the falling of the sparks.

In order to give a certain amount of light and to be steady and noiseless, the arc must be adjusted to a definite voltage and current. Therefore an arc lamp has to be provided with a regulating mechanism that automatically feeds the carbons as they burn out, and so keeps the distance between them constant. *The mechanism of multiple lamps needs to regulate for constant current only,* because the voltage between the wires is kept constant from the power house.

On the other hand, *a series lamp must regulate for constant voltage only,* since the current is kept constantly by means of special regulating devices in the power house.

The regulation of *multiple lamps* (sometimes called constant-potential lamps, since they burn on constant potential circuits) is usually brought about by an electro-magnet or solenoid that is connected directly in series with the arc. This colenoid operates either a clutch or clockwork device so as to feed the carbon when required. The simple arrangement shown in Fig. 3 is intended to illustrate some of the points connected with the operation of constant-potential lamps in general. By far the greater number of lamps in use employ a clutch rather than a clockwork feed. In Fig. 3, *t t′* are the lamp terminals connected across a constant-potential

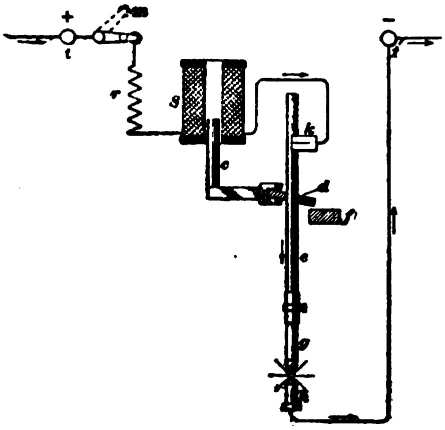

Fig. 8.

circuit; *r* is the resistance inserted to take up the surplus voltage and to make the action of the lamp stable; *S* is the solenoid connected in series with *r* and arranged to pull up the core *c* when current passes; *d* is the clutch, which is here shown simply as a washer with a hole attached; *f* is a stop against which *d* strikes when the core *c* lowers a sufficient amount; *g* is the top (positive) carbon and *h* the lower (negative). The current enters at *t*, passes through *r* and *S* to the brush *k*, which makes a sliding contact with the carbon rod, *e*. From *e* it passes to the top carbon *g*, thence to the lower *h*, and out at *t'*. The path is as indicated by the arrows. This is supposed to be a direct-current lamp; hence the current should flow, as shown, so as to bring the crater in the upper carbon. With an alternating-current lamp, it would, of course, make no difference how the lamp was connected.

When the current is off, *d* comes down against *f* and is tilted so that *e* slides through until *g* strikes *h*. As soon as the current is turned on by closing switch *m*, the core *c* is at once sucked up to the full limit for which the lamp is adjusted. As soon as *c* moves up *d* tilts, as shown in the figure, and grips *c*, thus raising *g* and striking or starting the arc. As the carbons burn, the arc gradually becomes longer and, consequently the resistance of the lamp, as a whole, increases. One fact which must not be lost sight of is that this lamp is connected in multiple across a constant-potential circuit; hence, as the arc lengthens, the current through the lamp is bound to decrease, no matter what current the other lamps on the same circuit may be taking. The result is that as the arc gets longer, *S* becomes weaker because of the smaller current, and *c* lowers a little. When *c* has moved a short distance, *d* comes in contact with *f*, and as *c* drops still farther, *d* is tipped a little and allows rod *e* to slide through. As soon as the carbons come nearer together, the current at once increases, *c* is pulled up, and the rod is held until the current becomes small enough to allow it to feed again. In this way the carbon is fed down, a little at a time, and the feeding is brought about by the decrease of the current due to the increase in the length of the arc. It is thus seen that the regulation of a constant-potential lamp may be brought about by the use of a simple series solenoid, or magnet, and as a matter of fact the mechanism of these lamps is very simple; some of the modern en-

closed-arc lamps have but little more mechanism than that indicated in Fig. 3.

When we come to consider the regulation of *series-arc lamps* and the mechanism necessary for their operation, we have a different problem to deal with. In the first place, when lamps are run in series, the current is always maintained at a constant value, or at least it should be if the regulating device in the power house works properly. It is evident, then, that a series-magnet alone is not able to do the regulating, because its pull remains the same no matter what might be the condition of the arc. Again, there must be some device in the series lamp that will preserve the continuity of the circuit in case a carbon should become broken, fall out, or the circuit through the lamp become broken in any way. If such a device is not provided, an open circuit in the lamp will result in all the lights on the circuit going out. This device is called a cut-out.

Although the current through the arc remains constant in a series system, the voltage across the arc increases as its length increases, and this increased voltage is made to bring about the regulation. Suppose that we modify the simple lamp shown in

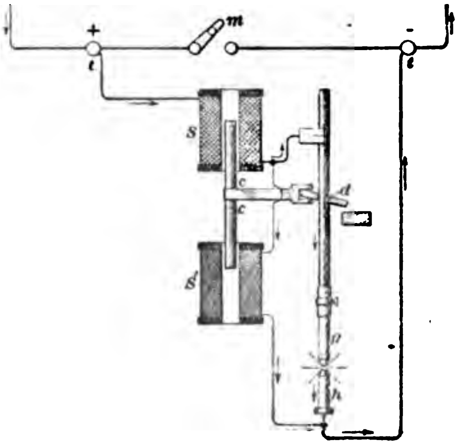

Fig. 4.

Fig. 3 by extending the core *c* downwards and adding another solenoid *S'*, as shown in Fig. 4. We can also omit the starting resistance *r*, as this is to be a series lamp, and there will be no excess voltage to be taken up; the current is maintained at a constant

value and resistance is not necessary to insure stability of operation. This second coil *S'*, is wound with a large number of turns of fine wire, so that when it is connected in shunt across the arc, as shown, but a small current will flow through it. The coils *S* and *S'* pull *c* in opposite directions; and *c* will always take up such a position that the two pulls are balanced. The action of the lamp is, then, as follows: When the lamp is out, the carbons *g* and *h* are in contact. Notice that the switch *m* in this lamp is connected across the terminals, and in order to put out the lamp, *m* is closed; this is just the reverse of the constant-potential lamp that is operated in parallel. When the lamp is thrown into circuit, the main current passes between *g* and *h,* but since the carbons are in contact there will be little or no drop in potential between them and, hence, practically no current will pass through the shunt coil *S'*. The result is that coil *S* pulls up the plunger, ***and*** in so doing lifts the upper carbon and starts the arc. The instant, however, that the carbons *g* and *h* separate, current flows through *S'*, because there is then considerable difference of potential between *g* and *h*. The result is that as the carbons are separated, the downward pull of *S'* becomes the stronger until it finally balances the upward pull of *S,* when the arc remains stationary. As the carbon burns away, the arc becomes longer; hence its resistance increases and the voltage across the arc increases. The pull of S does not change, because the main current is maintained constant from the power house. The pull of *S'* keeps increasing as the carbons burn away, and *c* is gradually pulled down until the lamp feeds. As soon as *g* feeds down the pull of S' decreases, because the arc shortens; hence, the position of *c* becomes again balanced, and so on, the plunger *c* moving back and forth through a small range between the coils. By properly adjusting the clutch, such a lamp may be made to keep the arc at the proper length within very close limits.

Figs. 3 and 4 give general schemes of construction only; actual lamps have some additional devices; for example an automatic cut-out when the carbons are burned out to a pre-determined length (in series lamps); a device for compensating changes of temperature of the coils, etc. It would be impossible here to go into all the details; it is believed that a clear understanding of the simple schemes shown in figs. 3 and 4 will enable the student to find out the

application of all the different parts in the actual lamps that they will have to work.

A short description is given below of two arc lamps of a popular make, in order to give an exercise in reading sketches and diagrams of circuits of arc lamps.

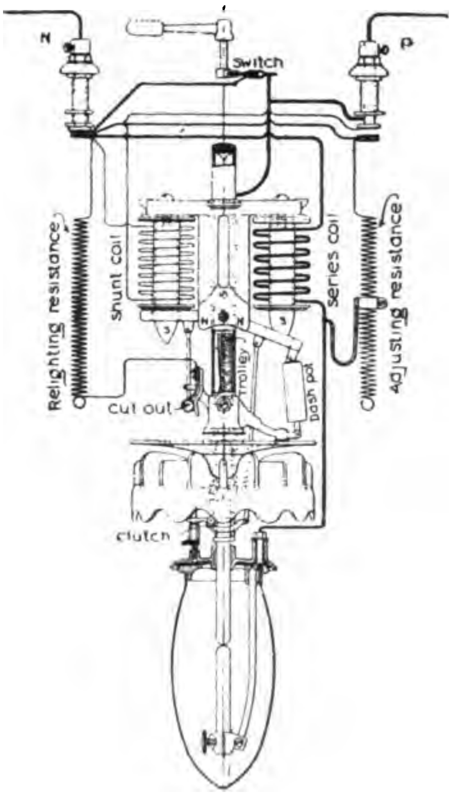

Fig. 5.

The lamp shown in Fig. 5 is a series enclosed direct-current arc lamp for street lighting. *P* is the positive terminal, *N* the negative; the main circuit is from the positive binding post to carbon tube, trolley, upper carbon holder and carbons, through the series coil and the adjusting resistance in parallel with it to the negative binding post. The shunt circuit is from the positive binding post through the shunt magnet coil to the negative binding post.

Opening the switch by turning it to the right puts the lamp mechanism in circuit. The carbons are normally together when the current is off. Turning the current on energizes the series magnet which attracts the armature carrying the clutch which grips and raises the upper carbon and establishes an arc. The adjusting resistance in parallel with the series coil permits more or less current to pass through the series coil, thus strengthening or weakening its effects on the armature. Counterbalancing the effect of the series magnet on the armature is the shunt magnet, which is affected by the entire difference of potential existing between the lamp terminals.

As the arc becomes too long the increased resistance between the terminals increases the voltage impressed on the shunt coil and consequently the current in the shunt coil, thus strengthening the shunt magnet which raises the shunt side of the armature. This lowers the other side with the clutch, shortens the arc, decreases the resistance between the terminals and allows the series magnet to again become effective in sustaining the proper length of arc.

If the series magnet draws too long an arc or the carbon fails to feed, the increased resistance of the arc causes the shunt magnet to become abnormally energized so that it closes the cut-out contacts and shunts the current around the lamp through the relighting coil. This action usually causes the carbons to drop together, after which the series magnet is again automatically cut into circuit and the arc re-established.

The rapid movement of the armature is prevented by the air dash-pot connected to one end.

The adjusting resistance not only permits the adjustment of the lamp voltage or the distance between the carbons within certain limits, but it also compensates for the influence of temperature. The resistance of the shunt coil becomes considerably higher after the lamp has been in operation an hour or two, than when the lamp is first started, consequently the current in the shunt coil decreases and it becomes too weak to counterbalance the action of the series coil. Now the series coil is shunted by the adjusting resistance made of material having a low temperature coefficient, for instance, of German silver; therefore, as the series coil becomes heated, more and more current flows through the resistance instead

of through the coil, so that the pull of the series coil is also decreased. With a correct design it is possible to maintain the same regulation of the hot lamp as when it is cold.

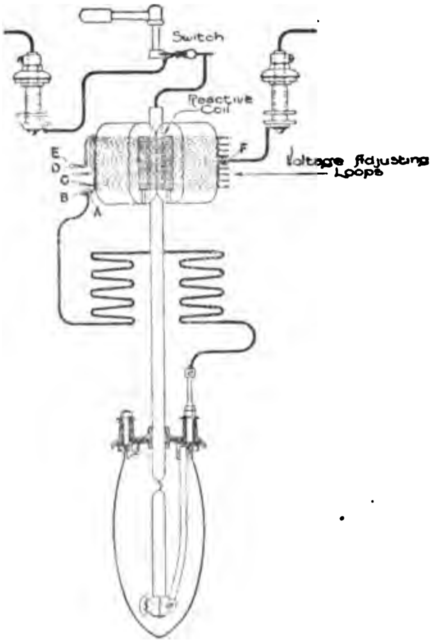

Fig. 6.

The lamp shown in Fig. 6 is a constant-potential or multiple arc lamp and has practically the same construction as the lamp shown in Fig. 3, except that being an alternating-current lamp it has a *reactive coil* for voltage adjustment, instead of the resistance *r* shown in Fig. 3, and the plunger is made from laminated iron. The lamp itself is supposed to burn at about 70 volts, the surplus of the voltage being taken by the reactive coil. The coil has several taps in order to enable the same lamp to be used on circuits with different voltages and different frequencies. An advantage of using a reactive or choke coil instead of a resistance is that the former consumes much less power; another advantage is that it takes less room and can be easily mounted on top of the lamp. The disadvantage of the reactive coil is that it lowers the power

factor of the system, and makes the regulation of the alternator more difficult.

The laboratory exercise should be begun by studying the construction and the circuits of a few exhibited lamps. Make clear to yourself the following points: is the lamp designed to be used on D. C. or on A. C. circuits and in parellel or in series with other similar lamps; where are the series and the shunt coils; by what mechanical transmission do they act on the clutch and consequently on the carbons; how are the carbons brought together when starting the lamp; is there any dash-pot and what does it act on; what occurs when the carbons become so short that the regulating mechanism can no more maintain the proper distance between them; are there in the lamp any mechanical or electrical means, by which its normal current and voltage can be adjusted at will, and in what do they consist. *Do not attempt to operate the lamps before you have made clear to yourself all these points,* because otherwise you cannot intelligently observe the performance of the lamp.

Now connect one of the lamps into the circuit in series with a regulating resistance and switch the current on. Adjust the current and the voltage until you obtain a good and steady light. If the lamp flickers, makes noise or in any other way behaves unsatisfactorily, try to find out to what it is due and remedy the fault if you can. Get the limits of voltage and current within which the lamp works satisfactorily, and determine the exact values of voltage and current at which in your opinion the lamp gives *the best service.*

It takes some time for the lamp to get into steady conditions; do not be in a hurry to take the readings immediately after the current is switched on for the first time. This is especially true for enclosed lamps, because the oxygen within the globe must first be used up and a definite gas mixture and temperature established. To see this clearer take off the inner globe and start the lamp in the open air; observe the difference in volts, amperes and in the quality and general appearance of the light. Before attempting to do this do not fail to introduce more resistance into the circuit. Also do not keep the current on with open arc more than a few

minutes, since the lamp takes under such conditions an excessive current.

It is a good scheme to have a short-circuiting switch around the ammeter; the lamps take a much larger current when just switched on; the ammeter pointer may swing beyond the scale and be damaged.

An important point upon which the satisfactory operation of arc lamps depends is *the quality of carbons* used; the best lamp will give a poor and unsteady light with inferior carbons. If time would permit the students should make a few simple tests for arc light carbons, as described in Foster's Pocket Book, pp. 396-397.

In your report make schematic sketches, like those in Figs. 3 and 4, and a short description of the lamps of which you investigated the construction. Give answers on the points asked on p. 10. For the lamps, on which you had current on, give the values of current and voltage and any peculiarities or faults observed during the operation. If carbons were tested state the results found. Those particularly interested in arc lamps will do well to make a thorough study of one of the good modern lamps in our collection (preferably outside of the regular laboratory time) and make a detailed drawing of it similar to that shown in Fig. 5.

2. *Series Arc-Light System.*

When arc lamps are scattered over a large territory, as for instance in lighting streets, they are usually connected in series, because of the simplicity of wiring and of a great saving in copper thus effected. With such a series system it is obviously necessary that *a constant current* be supplied from the center of distribution (power house or substation), since the same current flows through all the lamps and therefore individual lamps could not regulate its value. On the other hand each lamp must be provided with a regulating mechanism such as to maintain the required voltage at the lamp terminals. The station apparatus gives the total voltage necessary for operating a certain number of lamps in series, and each lamp has to take a proper amount of it.

The construction of series lamps and the mechanism by which they regulate for constant voltage were described above; here the

apparatus will be described by which a constant current is maintained in the circuit.

Both direct and alternating currents are used for series arc lighting; the regulating appliances are different in each case and will be described separately.

(1) *Direct-current constant-current dynamos.* Direct current used for series arc-lighting has a value of between 6 and 10 amps. and is supplied at a voltage from 500v. to several thousand volts according to the number of lamps in series. The power is generated by special machines, so called arc dynamos, provided with some kind of a solenoid operated device, which automatically maintains constant current. There are two drawbacks to this system; commutator troubles unavoidable with high voltages and the necessity of having special generators for arc lights only. These two disadvantages on one hand together with an always growing use of alternating currents on the other hand led in recent years to a preference being given to A. C. arc-light systems in new installations. Still there are a large number of D. C. arc dynamos in daily use in many power houses, and it is therefore desirable to have some knowledge of their construction and operation.

We have in our laboratory a Thomson-Houston arc dynamo, a two pole series-wound machine, which gives about 7 amperes at voltages from zero up to about 550v. Fig. 7 gives a general view

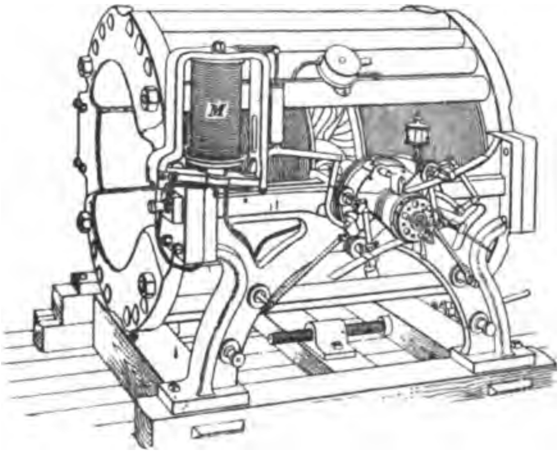

Fig. 7.

of the machine; Fig. 8 represents its armature winding and connections; the method of regulating is shown in Fig. 9.

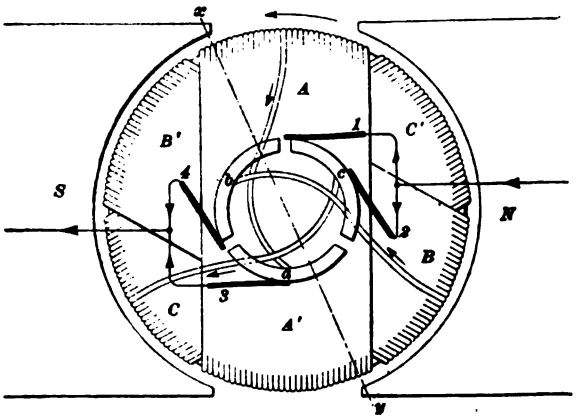

Fig. 8.

The armature is star-wound; it consists of three coils connected together on one end and each connected to a commutator segment on the other end. The machine has two positive and two negative brushes; this is necessary in order not to open the circuit when a brush jumps from one commutator segment to another; moreover by changing the distance between the brushes the voltage and consequently the current is regulated. The machine gives a unidirectional pulsating current rather than a direct current in the ordinary sense of the word; three commutator segments being by far insufficient to entirely smooth the pulsations of the alternating currents induced in the armature.

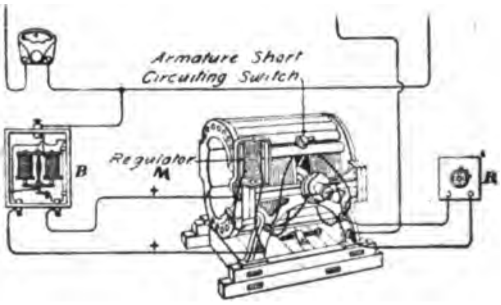

Fig. 9.

The brushes are connected to a rocker device which is in turn connected to the movable iron core of a solenoid *M* (Figs 7 and 9) called the regulator. This solenoid pulls the brushes apart when the current in the armature has reached a certain maximum value, and by the action of gravity the brushes are brought together again when the current falls below the predetermined amount. In order to bring this about an electro-magnet controller *B* (Fig. 9) is connected in the circuit with the regulator. The controller *B* is usually placed on the wall near the machine, and keeps the regulator magnet *M* short-circuited, in other words without action, so long as the main current is below its normal value. When the current rises beyond normal the core of the wall controller *B* is lifted up and in doing so it removes the short circuit of the brush-regulating magnet *M*. The current passes through the regulator and raising the core spreads the brushes farther apart reducing the voltage and consequently the current of the machine. A dash-pot is provided to prevent a too quick and jerky motion of the regulator.

Some other features of this machine are: An air-blast directed in the brushes and intended to suppress as far as possible the sparking inevitable with these machines; a rheostat *R* connected across the field winding of the machine in case hand regulation is desired; a non-industive resistance connected across the controller contact for the purpose of absorbing the kick due to the inductance of regulator circuit when the controller cuts it in or out.

The test on this machine consists in taking its load characteristics. A special load rheosfat is provided which has 20 equal resistances connected in series; each resistance is provided with a short-circuiting switch which cuts it out similarly to the short-circuiting device which cuts out a series arc lamp after the carbons have become too short. The 20 resistances are equivalent to as many arc lamps connected in series.

Begin the test on open circuit, when both amps and volts are zero; close the circuit on as high a resistance as possible and gradually reduce the number of lamps or equivalent resistances until the machine is short-circuited. The voltage of the machine is nearly proportional to the number of lamps in the circuit; the current remains constant within a wide range of voltages down almost to short-circuit of the machine. Plot amps and volts to the number of

lamps in the circuit as abscissae; or, which amounts to the same, use ohms in the external circuit as abscissae.

(2) *Constant-current transformer.* Commercial alternators supplying current for light and power are essentially constant potential machines, while constant current is required for supplying series arc lamps. The apparatus, which converts constant-voltage energy into constant-current energy and thus allows arc-light circuits to be fed from ordinary alternators, is called a constant-current transformer, sometimes also tub transformer or arc-lamp transformer.

An ordinary constant-current transformer is represented in Fig. 10 and also shown schematically in Fig. 11. The transformer in Fig. 11 has one primary and one secondary coil, while that in Fig. 10 is a larger size transformer and has two primary and two secondary coils.

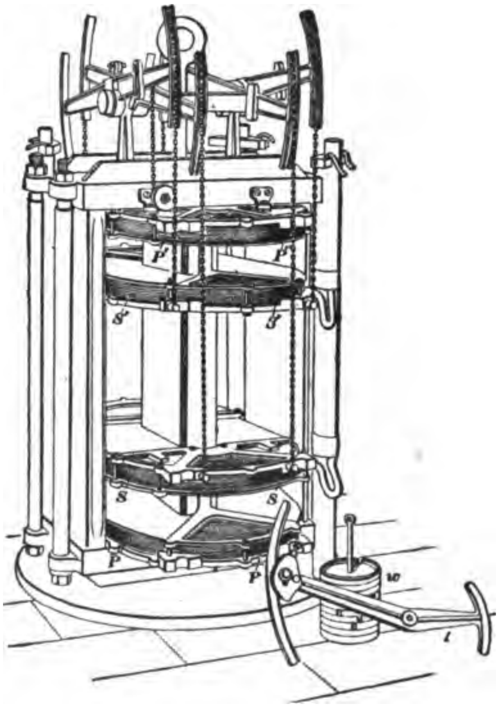

Fig. 10.

Referring to Fig. 11 *A A* is a laminated iron core built up in the same way as a core for an ordinary transformer. *P P* is the primary coil wound so as to be thin and flat and surrounding the central part of the core, as shown in the sectional view. This coil is fixed in position and is attached to the lines leading to the alternator that maintains a constant or nearly constant pressure across the terminals of the coil. *S S* is the secondary coil, which is also thin and flat. This coil is free to move up and down. It is suspended from quadrants on the end of a lever (see Fig. 10) and its weight is partially counterbalanced by weights hung on the other end. The terminals of the secondary are connected to the arc line by means of flexible cables that will not interfere with the free movement of the coil.

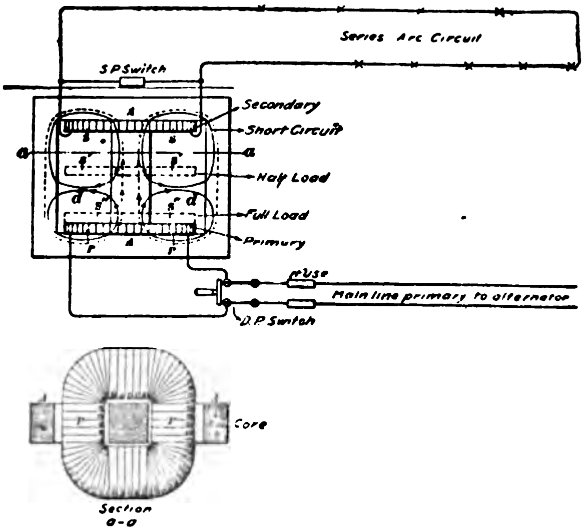

Fig. 11.

The action of the transformer is as follows: When the arc circuit is open and the primary is connected to the alternator, the secondary occupies the dotted position *S″ S″* resting on the primary. The apparatus will then act like an ordinary transformer; an alternating magnetic flux will be set up through the core, as indicated by the curved dotted lines, and a high e. m. f. will be generated in *S″ S″*, although no current can flow in it because the secondary cir-